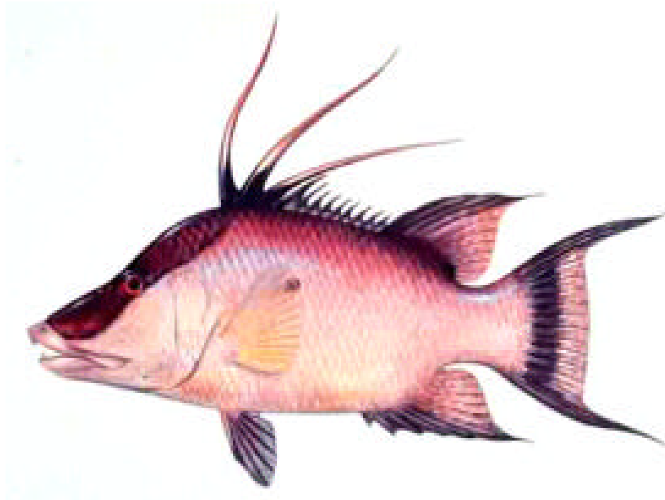
SEDAR6-RW-4

Florida Hogfish Fishery Stock Assessment



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FINAL REPORT

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Executive Summary

The Florida hogfish fishery is an economically-important part of the snapper-grouper complex of about 60 exploited reef fishes. As a consumer of shrimp, crabs and clams, hogfish play an essential ecological role within the larger multispecies reef fish community in the Florida coral reef ecosystem comprised of about 350 reef fishes and macroinvertebrates. Concern about the sustainability of the hogfish fishery has prompted a more in depth look at the status of the stock.

To conduct a stock assessment, we began with an exhaustive review of the scientific and technical literature, and a thorough assimilation of what were somewhat uneven data resources in space and time for hogfish. For this assessment, both fishery-dependent commercial and recreational catch-and-effort and fishery-independent design-based survey data were available. The fishery-dependent data resources (MRFSS and trip tickets) were available for the period 1982 to 2001 and appeared to have state-wide coverage, but significant catches were mostly restricted to south Florida waters. The available data were limited by incomplete time-series of nominal fishing effort, lack of clear delineation of the fishing gears used, and limited biological sampling of the hogfish population. The fishery-independent reef fish visual census (RVC) method database covers the period 1979-2002. The RVC database contains information on about 250 species of coral reef fishes, including most of those under exploitation in the Florida coral reef ecosystem. The RVC survey and analysis technology provides a precise and robust estimate of species abundance and size-structured biomass for the Florida Keys and Dry Tortugas.

Marine recreational fishing effort is very high in Florida with more than 30 million individual recreational fishing trips per year. The Florida total represents more than 35% of US annual total of marine recreational fishing trips. More than 15% of the Florida marine recreational fishing effort (i.e., 3.9 million trips per year) is directed at the coral reef ecosystem fishery. The quantity of nominal recreational fishing effort (day trips) generally dwarfs nominal commercial fishing effort for this species. Combined commercial and recreational hogfish landings for the period 1982-2001 have ranged as high as 272 metric tons (mt) in 1987, but has declined to a low of 61 mt during the 2000-2001 period. Recreational catches have declined from a high of 238 mt in 1987, then dropped to 154 mt in 1993, and they have averaged 61 mt in 1998-2001, even though the number of fishing trips has remained fairly constant over this entire period. Recreational fishery catches have averaged more than 3.5 times the level that of the commercial fishery per annum, while yields from both the commercial and recreational fishery sectors have been sharply declining.

We synthesized and standardized the population dynamic database on hogfish to improve understanding of their life history dynamics. Hogfish are protogynous (i.e., female first) hermaphrodites that live to a maximum age of 23 years. The all-tackle recreational world record hogfish was 8.84 kg (19 lb 8 oz) and landed near Daytona Beach, Florida, in April, 1962. Length dependent on age von Bertalanffy growth and allometric weight-length functions were developed for the Florida hogfish. The Florida von Bertalanffy growth function was very similar to that developed for hogfish in Cuban waters. The extensively synthesized population-dynamic database of hogfish demographic parameter estimates was considered to be at a level sufficient to conduct a comprehensive stock assessment and fishery risk assessment.

We used a suite of age-based, length-based and biomass-dynamic assessment models in conjunction with the fishery-dependent and fishery-independent data and population dynamic estimates to conduct a formal fishery stock assessment on hogfish. The average size in the exploitable phase independently estimated from RVC, MRFSS, headboat and BNP creel intercept survey data were very similar during the period 1976-2002. The age-based, length-based, and biomass-dynamic assessment models gave quite similar estimates of fishing mortality rates, and the various methodologies agreed very well in overall temporal trends. In fact, all the estimation methodologies led us to the same conclusion. That is, the results of these extensive analyses suggest that the Florida hogfish stock is currently overfished, and probably has been for at least the last two decades. Estimated current total fishing mortality rate estimated at F=0.57 conservatively places exploitation of the hogfish stock to be at greater than 4 times the level that produces maximum sustained yield, the national standard for sustainable fisheries. To calibrate these estimates of fishing mortality rates for the Florida hogfish stock, we used a sex-differentiated age-structured stochastic length-based population simulation model, REEFS, to conduct a thorough analytical yield management benchmark analysis and risk assessment. The Florida hogfish stock biomass is presently at about 26% of the level that produces MSY; and, the current spawning potential ratio (SPR) is only about 9 percent of historical level. In general, the hogfish stock was at a relatively low level of spawning biomass at the beginning of the period of analysis (i.e., 1979), seemed to have recovered a bit in the early 1990s, then declined again. A perceivable increase in recruitment was noted in the late 1990s through 2002. This increase may have been associated with management efforts like increased size limits, trap reductions, and/or imposition of closed areas. Perhaps the most striking result from these analyses was that the recreational fishery presently generates more than 85 percent of the total fishing mortality on the Florida hogfish stock.

We recommend that an immediate management action should be to raise the minimum size limit to about 20 inches FL to eliminate the growth overfishing that is presently occurring in the fishery. Another obvious need is to reduce the rate of total fishing mortality being imposed on the stock by recreational and commercial fishery sectors. In fact, we estimate that spear fishers (both recreational and commercial) are the major sources of hogfish fishing mortality. Hence, a further recommendation would be to either restrict this sector to fishing in particular areas by perhaps limiting the use of SCUBA with spearfishing (this could provide some depth protection), establish smaller bag limits (e.g., 1 fish), and/ or limit the amount of time during a year that spear fishing gears may be used.

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1. GENERAL BIOLOGICAL CHARACTERISTICS

1.1 Fishery Ecology

The Florida hogfish, *Lachnolaimus maximus*, commonly referred to as the “hog-snapper”, is a member of the wrasse family (Labridae). In Florida, hogfish are primarily found in the warm subtropical and tropical waters of the coral reef ecosystem; however, hogfish have a recorded range from Nova Scotia, Canada, to northern South America, to Bermuda, the Caribbean Sea and the Gulf of Mexico. In the coral reef ecosystem hogfish are primarily associated with shallow (i.e., 3-30 m), low relief (<1.5 m) mixed hardbottom-seagrass and patch reef environments (Robins and Ray 1986, Randall 1996).

In Florida, juvenile hogfish have been reported from Florida Bay in winter and spring (Tabb and Manning 1961), in Biscayne Bay *Thalassia* beds during summer (Roessler 1964), and in the Marquesas region during July (C. Messing, pers. comm.). Larger mature fish are normally found on the reefs, although hogfish are often encountered where gorgonian covered low-relief hardbottoms are found (FISHBASE www.fishbase.org 2003, Franklin et al. 2003). Such observations suggest ontogenetic migrations occur between the shallow coastal lagoons that serve as nursery areas for juveniles that ultimately migrate to the offshore coral reef and hardbottom habitats as mature adults.

Hogfish forage by day on benthic invertebrates such as crabs, bivalves, gastropods, and sea urchins in hardbottom areas adjacent to coral reefs (Gomon 1978, Claro et al. 1989, Sierra et al. 1994). A dietary preference for these herbivore and detritivore groups appears to make hogfish susceptible to accumulation of ciguatoxins. Several authors have reported cases of ciguatera poisoning from consumption of hogfish in Florida (de Sylva 1994), Puerto Rico (de Motta et al. 1986), St. Bart, St. Martin, Anguilla (Bourdeau 1991), and the U.S. Virgin Islands (Dammann 1969, Brody 1972, Halstead 1970, Olsen et al. 1984). Hogfish are highly esteemed as food fish (Gomon 1978). Worldwide, fishing pressure has reduced many populations to critically low levels such that the species has been identified as vulnerable to extinction by the IUCN (e.g., IUCN 2000). In Florida, the fishery is economically-important to both commercial and recreational fisheries due to the unique taste and flavor of hogfish.

1.2 Life History and Population Dynamics

We conducted an exhaustive synthesis of the scientific and technical literature on hogfish to develop the most comprehensive and accurate database on key demographic and population dynamic characteristics. Such data necessary to conduct a full stock assessment and fishery risk analysis.

1.2.1 Age and Growth

Until recently, very little was known about lifetime growth patterns of hogfish. McBride (2001) conducted an empirical study of lifetime growth of hogfish by obtaining age information from otoliths taken from animals sampled from the southeastern Gulf of Mexico (i.e., west Florida shelf and Tortugas region) and the Florida Keys. He found that hogfish from the eastern Gulf of Mexico reached older ages (up to 23 yrs) and on average had larger size-at-age individuals than those from the Florida Keys (maximum of 13 yr). With the data of McBride (2001), we used nonlinear regression techniques to estimate parameters of the von Bertalanffy growth equation for both the eastern Gulf of Mexico and the Florida Keys (**Figure 1.1**). The Florida Keys and eastern Gulf of Mexico models were very different. However, the von Bertalanffy growth equation for Cuban hogfish reported by Claro et al. (2001) was very similar to our eastern Gulf of Mexico model (**Figure 1.2**). It is unlikely that differences between the eastern Gulf of Mexico and the Florida Keys growth models can be attributed to differences in physical oceanographic conditions (e.g., temperature regimes), as these same differences are observed between the Florida Keys and Cuba. Because observed differences between the Florida Keys and eastern Gulf of Mexico growth curves become readily apparent after hogfish reached the regulated size-at-first-capture (i.e., L_c=275 mm FL), we believe that these observed differences were most likely due to differences in fishing pressures. As a result, we used the eastern Gulf of Mexico growth function as our Florida hogfish growth model to provide a reliable predictor of lifetime growth (c.f., **Figure 1.2**).

We also used nonlinear fitting techniques to estimate the parameters of the allometric weight on length function (**Figure 1.3**). **Table 1.1** summarizes the von Bertalanffy growth at age functions estimated from the Florida data of McBride (2001) and that given by Claro et al. (1989) for Cuba. Weight at age was obtained by transforming length at age from the von Bertalanffy model by the allometric model. The combined growth model suggests that the average hogfish at 23 years has a maximum size L_λ of 786 mm FL and maximum weight W_λ of 9.14 kg. Reported maximum length reported for a male hogfish was 910 mm TL (Robins and Ray 1986); while the maximum reported weight was 10 kg (22 lb) (Cervigon et al. 1992). The largest hogfish ever landed on hook-and-line weighed 8.84 kg (19 lb 8 oz) was caught in 1962 off Daytona Beach, Florida (IGFA 2003).

1.2.2 Maturity and Reproduction

Hogfish are dichromatic, protogynous hermaphrodites that exhibit sexual dimorphism (Davis 1976). The common name of this species, *hogfish* or *hog-snapper*, refers to the elongate pig-like snout that is typical of large males, which is lacking in younger smaller females. Coloration is quite variable, depending on age, sex, and habitat. Males also exhibit dark markings on the top of the head and along the base of the medial fins, and a dark spot behind the pectoral fin (Colin, 1982). Hogfish bear 3 first dorsal filamentous spines, a unique characteristic among wrasses (Smith 1997). In general, fish below the minimum size of first capture (i.e., < 304.8 mm TL or 12 in) are primarily females that most likely have not yet reproduced. Studies of gonadosomatic index (GSI) conducted by Davis (1976) indicated that spawning occurred from September to April, with a February and March peak. Davis (1976) showed that fecundity increased approximately linearly with weight, and exponentially with length. He estimated a mean relative fecundity of 158.3 ova/g and proposed the fecundity function: $Eggs=0.00246FL^{3.05}$. Davis' (1976) study also provided us with data suitable for a logistic regression to estimate proportion female at size (FL):

$$p(fraction\_\ female) = \frac{e^{(b_0+b_1FL)}}{1+e^{(b_0+b_1FL)}} \tag{1.1}$$

where b_0 and b_1 are parameters of the logistic regression model (i.e., b_0 = 4.4601, and b_1 = -0.00952), and FL is fork length. Age-specific relations are shown in **Table 1.2b** and **Figure 1.4**.

Around the region, in Cuba's Gulf de Batabano, spawning season for hogfish is May, June and July (Garcia-Cagide et al. 1994). The gonadosomatic index (GSI) was 2.43% with mean relative fecundity of 257 oocyte / g. Hogfish were observed to be continuous asynchronous spawners with multiple batches of 39,000 oocytes over a four-five month period (Claro et al

1989). Sex ratios (male:female) among hogfish varies in Puerto Rico, Florida and Cuba, from 1:3, 1:5, and 1:10, respectively. These ratios may reflect a variety of differential fishing pressures at each of the study sites (Davis 1976, Colin 1982, Claro et al. 1989).

Selection by fishing at relatively high exploitation rates reduces the abundance of large mature fish, making a stock young through a process known as "juvenesence". Recent work in the South Florida coral reef ecosystem has shown that hogfish are susceptible to exploitation effects like "juvenescence" (Ault et al. 1998), a phenomena that leads to decreased per capita fecundity (McBride 2001, McBride and Murphy 2003).

1.2.3 Life Span, Mortality and Survivorship

McBride's (2001) estimate of 23 years for maximum age by use of life span methods indicates that the natural mortality rate is M=0.13025 (Ault et al. 1998) (**Table 1.2a**). The age-specific survivorship is given in **Table 1.2b** and **Figure 1.4**. The Lorenzen (1997) survivorship at age was developed according to a empirical relationship between body weight and natural mortality rate. Survivorship reflects the annual probability of living to a given age.

1.3 Parameter Synthesis for Stock Assessment Modeling

The synthesized population-dynamic database of parameter estimates and variable definitions is found in **Table 1.2.** Length at age was estimated using the von Bertalanffy model with the parameters estimated from the data of McBride (2001) (**Table 1.2b**). Fecundity at size was determined by the relationship of Davis (1976). Weight at age was determined by applying the allometric growth function to the expected length at age relationship. The proportion female at age was given by the logistic regression model developed from data of Davis (1976). The proportion mature at age was determined from maturity data provided by McBride (2001). The expected vulnerability at age was estimated by a separable logistic function from the growth data with the size of 50% maturity being set at 165 mm FL according to McBride (2001) (C.J. Walters, pers. comm.). Finally, the numbers of eggs produced per female at age was determined by the fecundity times the fraction mature. Overall, we deemed the parameter database for hogfish to be sufficient to conduct a comprehensive stock assessment and fishery risk analysis.

2.0 FISHERY CHARACTERISTICS AND POPULATION ABUNDANCE INDICES

2.1 Data Sources

Two major classes of fishery database resources (i.e., fishery-dependent and fishery-independent) were explored and analyzed to provide sufficient resource information to conduct a stock assessment for Florida hogfish. Fishery-dependent database resources included those from the recreational and commercial fishery sectors.. The primary data source for the recreational fishery was the national Marine Recreational Fisheries Statistics Survey (MRFSS) for Florida covering the period 1982 to 2001. We obtained MRFSS data from the Florida Marine Research Institute (FMRI). The MRFSS survey has two main components. The first is a telephone survey of households to collect general information on recreational fishing activity. The second component is an intercept (i.e., creel) survey of recreational fishers to collect more specific data on catch, effort, gear, species composition, lengths and weights of harvested fish, etc. Supplementary recreational fishery data were obtained from intercept surveys of anglers on headboats (large fishing party charter boats) in the Florida Keys during 1978 to 1999, and fishers at boat ramps in Biscayne National Park (BNP) for the period 1976 to 1998.

Commercial fishery data on hogfish were obtained from FMRI's Trip Ticket database for the period 1985 to 2001. This database provides information on catch by species, effort, gear, etc., for commercial fishing trips that sold the catch to licensed seafood dealers in Florida.

Fishery-independent data on hogfish were obtained over the period 1979-2002 from the reef fish visual census (RVC) using the stationary cylinder method (Bohnsack and Bannerot 1986) conducted by NOAA Fisheries and University of Miami RSMAS scientists in the Florida Keys reef track. Survey data on species density (number of fish per unit area) and length composition were collected by standard, non-destructive, *in-situ* visual monitoring methods by highly trained and experienced divers using open circuit SCUBA (Bohnsack et al. 1999).

2.2 Fishing Trips and Landings

2.2.1 Recreational Fleet

The MRFSS database provides estimates of total marine recreational fishing trips in Florida by the following stratification variables:

Years:	1982-2001
Wave:	2-month period; 6 total 'waves' in 1 year
Subregion:	(1) Florida west coast and Florida Keys; (2) Florida east coast
Fishing Mode:	(1) shore, jetty, pier, etc.; (2) charter boat; (3) private or rental boat

Total trips for years 1982-2001 are graphed in **Figure 2.1**. There has been a general increase in marine recreational fishing activity in Florida over the past 20 years, from about 15-20 million individual trips in the early 1980s to about 25-30 million trips in the early 2000s.

The number of marine recreational trips targeting hogfish was estimated in the following manner. Trip records of the MRFSS intercept database were categorized into three types: (i) trips that captured hogfish (positive catch trips); (ii) trips that did not capture hogfish, but targeted or captured principal species in the snapper-grouper complex of reef fishes (potential zero catch trips); and (iii) other trips. Positive catch trips were analyzed with respect to fishing gear, fishing mode (shore or boat), and county. Hogfish were captured with two gears, hook-and-line and spear. Spear trips were of 'boat' mode only. Hook-line trips were predominately 'boat' mode as well, but there were some 'shore' mode trips that captured hogfish. Hogfish were captured in 25 of 35 Florida coastal counties according to MFRSS intercept data (**Figure 2.2**). The majority of intercepts of trips capturing hogfish occurred in southern Florida (both east and west coasts and Keys). Using the 'potential' zero catch hogfish trip records as a starting point (category (ii) records), the following procedure was employed to further isolate reef fish trips that could have captured hogfish but did not:

<u>Step 1:</u> Reef fish trips using gears other than hook-line or spear were eliminated from consideration (i.e., changed from category (ii) 'potential' trips to category (iii) 'other' trips).

<u>Step 2:</u> Reef fish trips from counties in which no hogfish were captured over the 20-year period (1982-2001) were eliminated from consideration.

<u>Step 3:</u> Reef fish trips for the gear-mode combination of 'hook-line' and 'shore' were eliminated from consideration for counties with no positive catch hogfish trips of this type.

The resulting 'zero catch' reef fish trips were combined with the positive catch hogfish trips to obtain the overall number of valid 'reef fish trips', which we define as fishing trips targeting the snapper-grouper complex that could have resulted in capture of hogfish. The total number of MRFSS intercepts and sampled fishing trips by year, along with the number of reef fish intercepts and sampled trips for hook-line and spear gears are provided in **Table 2.1**. Note that a single ‘intercept’ of a fishing party (1 interview per party) often collects information on multiple individual ‘trips’ (1 trip per individual fisher).

Recreational reef fish trips were estimated by the formula,

$$\text{reef fish trips} = \text{total estimated trips} \times \left(\frac{\text{sampled reef fish trips}}{\text{all sampled trips}} \right) \qquad (1.2)$$

Computations were initially carried out for each year and gear by subregion-mode strata. This required two modifications to the original stratification scheme of the MRFSS total estimated trips database: (1) fishing mode was collapsed to two types, shore or boat; (2) wave strata were collapsed to annual time periods. Annual totals by gear were then obtained by summing over subregion-mode strata (**Table 2.2a**). Annual recreational reef fish trips (gears combined) are plotted in **Figure 2.1** (also listed in **Table 2.2b**). Estimated recreational reef fish trips have been quite stable over the past 10-15 years at approximately 4 million trips per year. Reef fish trips have accounted for about 15-20% of total marine recreational trips in Florida each year.

Nominal fishing effort in units of person-hours was obtained by multiplying the time spent fishing (in hours) by the number of participants for each trip in the intercept survey. Missing values of trip fishing times were estimated by the median hours fished for each gear-mode combination: 3.5 h for shore mode hook-line trips; 4.5 h for boat mode hook-line trips; and 2.0 h for boat mode spear trips. (The frequency distribution of fishing times was highly skewed; consequently, the median value is a better measure of central tendency compared to the mean value.) Recreational nominal fishing effort for reef fish was estimated by

$$\text{reef fish effort} = \text{total estimated trips} \times \left(\frac{\text{sampled reef fish effort}}{\text{sampled reef fish trips}} \right) \qquad (1.3)$$

As for the estimation of reef fish trips, computations were initially carried out for each year and gear by subregion-mode strata. Annual totals by gear were then obtained by summing over subregion-mode strata. Recreational hogfish catch in numbers was then obtained by

$$\text{hogfish catch} = \text{reef fish effort X} \left(\frac{\text{sampled hogfish catch}}{\text{sampled reef fish effort}} \right) \tag{1.4}$$

These computations were also initially carried out for each year and gear by subregion-mode strata. Annual totals by gear were then obtained by summing over subregion-mode strata. Sublegal hogfish that were caught and released were excluded from the catch computations. Hogfish catch in weight was obtained by multiplying catch in numbers by mean individual weight. Annual mean weight was estimated from MRFSS intercept survey records of individual hogfish weight measurements. Weight observations were log-transformed prior to estimation to account for the skewed frequency distribution resulting from the minimum length at capture regulations. Back-transformed estimates of annual mean individual weight of captured hogfish and associated standard errors are given in **Table 2.3**. Annual estimates of nominal reef fishing trips and hogfish catch in weight (gears combined) are provided in **Table 2.2b**. Over the past 10 years, recreational hogfish catches have declined from a high of about 200 metric tons (i.e., 238 mt) in 1987 to an average of 187 mt per year in 1992-1993 to about 60 mt per year for 1998-2001, even though the number of fishing trips remained fairly constant during 1991-2001.

2.2.2 Commercial Fleet

As was done for the recreational fleet, it was necessary to account for all commercial trips that could have resulted in capture of hogfish. As a first step, all trips from the trip ticket database that reported catch of hogfish were analyzed with respect to geographical fishing regions (Florida counties) and gears. Since trip ticket data prior to 1991 lacked gear information, records for the period 1991-2001 were utilized for this analysis. Counties with 3 or more commercial trips reporting hogfish catches over the 1991-2001 time frame are denoted in **Figure 2.2**. Southern Florida coastal counties stretching from Pinellas on the west coast to Palm Beach on the east coast accounted for 87% of positive catch hogfish trips. Monroe County alone, which includes the Florida Keys, accounted for 60% of positive catch trips. Three primary gears captured hogfish: hook-line, spear and fish traps. There were also two ‘combination’ gears with a substantial number of records, hook-line plus spear, and hook-line plus traps (trip tickets report only 1 gear category per trip; when more than one gear was used, a combined gear category is reported). These five gear types accounted for 80-90% of positive catch hogfish trips. A number of other gear types, including many varieties of combination gears, captured hogfish, but there were very few individual trips for each single type. These were combined into an 'other' category for our analysis. A final gear category was 'not reported', trips with no gear information. This category contained the majority of hogfish positive catch trips in 1991 and 1992, but from 1993 on the number of trips lacking gear information dropped substantially.

The total number of commercial hogfish trips is the sum of positive catch trips and valid zero catch trips. The following procedure, similar to the procedure described above for the recreational fishery, was used to designate valid zero catch hogfish trips:

Step 1: FMRI provided trip ticket data for trips capturing species in the snapper-grouper complex of reef fishes but not capturing hogfish. This was the 'starting' zero catch dataset.

Step 2: Trip records from the zero catch dataset were eliminated for counties with no reported commercial hogfish landings, and also for counties with fewer than 3 positive catch trips over the 1991-2001 time frame.

Step 3: Trip records with gears that never captured hogfish were eliminated.

The annual number of estimated commercial fishing trips targeting hogfish by gear type are provided in **Table 2.2a**. Total commercial hogfish trips (gears combined) and catch by year are given in **Table 2.2b**. From 1989 to 1993, commercial hogfish trips ranged between 100,000 to 140,000 per year producing annual catches of about 50-60 metric tons. Commercial hogfish trips have declined since then to 50,000 to 60,000 per year for 2000-2001, producing much lower catches of around 20 metric tons.

Nominal fishing effort in units of trip-hours was computed for hook-line and spear fishing gears. (Trip-hours is used rather than person-hours since the number of persons participating in a given fishing trip is not reported on trip-ticket forms). For trips recording time units in hours, the nominal effort was the reported trip duration. For trips recording time units in days, nominal effort was computed by multiplying trip duration (in days) by the median hours fished for one-day trips (trips recorded in hours with durations less than 24 h) by gear type. As for the recreational fishery data, missing values of trip durations were estimated by the median duration time for each gear. Median duration times were estimated separately for positive hogfish catch trips and zero catch trips.

Nominal fishing effort for traps would ideally be computed in units of soak-hours per individual trap; unfortunately, the majority of trap gear records had incomplete information for the number of traps fished and/or time spent fishing (trip duration or soaktime). The number of trips was thus considered the unit of nominal effort for traps. Likewise, trips were designated as the nominal effort unit for combination gears (hook-line plus spear, hook-line plus traps), other gears, and trips with missing gear information (**Table 2.2**).

2.3 Effort Standardization Among Fleets and Gears

To understand the relative exploitation potential of recreational and commercial fleets comprising the hogfish fishery in Florida, it was necessary to standardize nominal fishing effort among fleets and gear types. We employed the 'fishing power' method of Robson (1966) to carry out the standardization. This approach has deep roots in traditional fish population dynamics theory (Beverton and Holt 1957; Ricker 1975). Catch C in number of animals is related to average population abundance $\overline{N}$ in a specified time interval by

$$C = F\overline{N} = qf\overline{N} \tag{2.1}$$

where F is the instantaneous rate of fishing mortality, defined as the product of nominal fishing effort f and catchability coefficient q, the fraction of the stock removed per unit of nominal fishing effort. Catch-per-unit-effort (CPUE), a relative index of population abundance, is

$$\frac{C}{f} = q\overline{N} \tag{2.2}$$

When dealing with multiple fishing gears operating on the same unit stock, fishing mortality for each gear j can generally be described by

$$F_j = q_j f_j \tag{2.3}$$

with overall F computed as

$$F = \sum_j q_j f_j \tag{2.4}$$

Catchability may differ substantially among gears; in addition, nominal effort may be measured in different units for different gears (e.g., angler-hours, trap soak-hours, etc). The "fishing power" method was developed to estimate the relative catchability among different gears, fleets, etc. This approach was originally conceived by Gulland (1956) and Beverton and Holt (1957), and then formalized statistically by Robson (1966). Fishing power models usually ascribe variation in CPUE to two main factors: (1) the times and locations of sampling effort; and, (2) the type of sampling gears (or vessels) employed. CPUE for time-location *i* and gear *j* can thus be estimated by a model of the form

$$CPUE_{ij} = \alpha + b_i + g_j + \varepsilon_{ij} \tag{2.5}$$

where α is a constant, b_i is a time-location coefficient, g_j is a gear coefficient, and ε_{ij} is an additive error term.

Following Robson (1966), a general linear model for estimating the parameters of equation (2.5) for time-locations *i*=1,2,..., *h* and gears *j*=1,2,..., *k* is

$$y = \alpha + b_1 X_1^{(b)} + \ldots + b_{h-1} X_{h-1}^{(b)} + g_1 X_1^{(g)} + \ldots + g_{k-1} X_{k-1}^{(g)} + \varepsilon \tag{2.6}$$

where the parameters to be estimated are intercept α, time-location coefficients b_i's, and gear coefficients g_j's. The independent variables X's are discrete categorical or "dummy" variables, $X_i^{(b)}$'s for time-locations and $X_j^{(g)}$'s for gear types. Dummy variables are coded as for a standard two-way analysis of variance (ANOVA) model (cf. Robson 1966 or Ault and Smith 1998 for example dummy variable coding schemes), which imposes the following ANOVA restrictions

$$\sum_{i=1}^{h} b_i = 0$$
$$\sum_{j=1}^{k} g_j = 0 \tag{2.7}$$

for the b_i and g_j model parameters. Thus in equation (2.6), *h*-1 time-location parameters and *k*-1 gear parameters are estimated, and the remaining parameters $b_{i=h}$ and $g_{j=k}$ are obtained by

$$b_h = -\left(\sum_{i=1}^{h-1} b_i\right)$$
$$g_k = -\left(\sum_{j=1}^{k-1} g_j\right) \tag{2.8}$$

following the constraints of equation (2.7). Our principal focus is to obtain accurate and precise estimates of gear parameters g_j's from equation (2.6). The coefficients b_i's are included in (2.6) to control for temporal and spatial variation in CPUE. The model-predicted CPUE for gear *j* is estimated by

$$CP\hat{U}E_j = a + g_j \tag{2.9}$$

Fishing power, which we denote as the 'gear calibration factor' for gear *j*, GCFj, is estimated as the ratio of the model-predicted CPUE for gear *j* to the model-predicted CPUE of a standard gear (i.e., *j*=S),

$$GCF_j = \frac{CP\hat{U}E_j}{CP\hat{U}E_S} \tag{2.10}$$

In this formulation, any gear can be selected as the standard. Standardizing nominal effort among multiple gear types is then carried out by multiplying each effort value by its associated GCF_j.

For application to the Florida hogfish fishery-dependent data, commercial and recreational catch and effort trip records were first combined into a single dataset. This dataset contained nine different fishing gears, seven for the commercial fleet and two for the recreational fleet (**Table 2.4**). Data for the fishing power ANOVA model (equation 2.6) are organized as for a randomized block experimental design in which the main blocking variable is a combination of time and location. Space-time blocks were designated as follows:

Time: year and season (4-month time intervals: Jan-Apr, May-Aug, Sep-Dec)
Space: county

The observational unit was block CPUE, computed as the sum of catch divided by the sum of nominal effort within a given block, for each gear. Further restrictions on CPUE observations were imposed to meet data requirements of the two-way ANOVA model. For each block, the following procedure was carried out sequentially:

(i) only include observations for gears with positive CPUE values;
(ii) only include the space-time block if two or more gears were fished.

The parameters of equation (2.6) were estimated using ordinary least-squares regression (Neter et al. 1996). Prior to estimation, CPUE observations were log-transformed to meet the normality requirement of the residual errors (i.e., y=log(CPUE) in equation 2.6). Parameter estimates and standard errors for the gear coefficients g_j's and intercept α are given in **Table 2.4**. Model-predicted log(CPUE) values for each gear were estimated using equation (2.9); these estimates were back-transformed to yield predicted CPUEs. Commercial spear was chosen as the standard gear. The GCFs for each gear were computed using equation (2.10), and were used to standardize nominal effort for each commercial and recreational gear type. The unit for standardized effort is thus commercial spear trip-hour. The overall set of standardized fishery catch and effort data for the commercial and recreational fleets for the period 1982 to 2001 in given in **Table 2.5**.

2.4 Catch and Effort Statistics

Hogfish catch, standardized effort, and CPUE for recreational gears are compared in **Figure 2.5**. Annual CPUE was computed as the sum of annual catch divided by the sum of annual effort by gear. For the first 10 years of the time-series, catch and effort were somewhat erratic, but more so for spear gear. This is likely due to lower sample sizes in the MRFSS intercept survey during this period (**Table 2.3**). For the period 1991-2001, there was a substantial increase in MRFSS intercept sample sizes. Standardized effort for 1991-2001 was similar for hook-line and spear gears except for the last two years, 2000 and 2001, in which hook-line effort was higher (**Figure 2.3b**). Spearfishers, however, produced consistently higher catches (**Figure 2.3a**) and exhibited higher CPUE (**Figure 2.3c**) compared to hook-line anglers. This is rather remarkable given the wide disparity in the number of fishing trips between the two gears, with the number of trips for hook-line anglers 35-45 times higher per year than trips for spearfishers (**Table 2.3a**).

Catch, effort, and CPUE for commercial gears are compared in **Figure 2.4** for the period 1991-2001. Gear category NR (not reported) accounted for the majority of effort during 1991-1992. From 1993 on, spear, trap, and hook-line were the major gear types with respect to fishing effort (**Figure 2.4b**), accounting for the majority of the catch as well (**Figure 2.4a**). Of these three principal gears, spear had consistently higher catches and effort for 1996-2001. With the exception of the minor gear type hook-line plus traps, CPUE gradually declined for the major gears from 1993 to 1999, followed by a slight increase for 2000-2001 (**Figure 2.4c**).

In **Figure 2.5**, hogfish catch, effort, and CPUE are compared for the recreational and commercial fleets. Since 1991, recreational effort has been substantially higher than commercial effort (**Figure 2.5b**). Recreational catch has also been consistently higher than commercial catch in all years since data for both fleets have been recorded (**Figure 2.5a**). From 1990-2001, the period corresponding to improved data quality for both fleets (higher sample sizes for recreational, more complete gear information for commercial), annual CPUE is quite consistent between the fleets. CPUE, an index of population abundance for hogfish at or above legal capture size, exhibited an increase from 1990 to 1993, and then a decline from 1993 to 2000.

2.5 Fishery-Independent Survey Analysis

The fishery-independent reef fish visual (RVC) survey in the Florida Keys employed a two-stage stratified random sampling (StRS) design (Cochran 1977). Stratification was based on a combination of cross-shelf reef classification and depth (**Table 2.6a**). The stratification scheme evolved over the survey time period 1979-2001 (Ault et al. 2002), as summarized in **Table 2.6b**.

The primary measure is fish density *D*, the number of individuals observed per diver station, i.e., number per 177 m^2 (the area of the basic sampling unit). Fish density D_{ij} at each diver station *j* (i.e., the second-stage unit) in primary unit *i* was obtained by averaging densities for the buddy team of divers (usually two divers but sometimes three). Mean density within primary unit *i* in stratum *h* was estimated by

$$\overline{D}_{hi} = \frac{1}{m_{hi}} \sum_{j} D_{hij} \tag{2.11}$$

where m_{hi} is the number of diver stations in primary unit *i* and stratum *h*. Stratum mean density was computed as

$$\overline{\overline{D}}_{h} = \frac{1}{n_{h}} \sum_{i} \overline{D}_{hi} \tag{2.12}$$

where n_h is the number of primary units sampled in stratum *h*. The sample variance among primary unit means in stratum *h* was estimated using

$$s_{1h}^{2} = \frac{\sum_{i} \left(\overline{D}_{hi} - \overline{\overline{D}}_{h} \right)}{n_{h} - 1} \tag{2.13}$$

and the stratum sample variance among diver stations within primary units was estimated as

$$s_{2h}^{2} = \frac{1}{n_{h}} \sum_{i} \left[\frac{\sum_{j} \left(D_{hij} - \overline{\overline{D}}_{hi} \right)}{m_{hi} - 1} \right] \tag{2.14}$$

The variance of mean density in stratum *h* was then estimated by

$$\operatorname{var}\left[\overline{\overline{D}}_h\right] = \frac{\left(1 - \frac{n_h}{N_h}\right)}{n_h} s_{1h}^2 + \frac{\frac{n_h}{N_h}\left(1 - \frac{m_h}{M_h}\right)}{n_h m_h} s_{2h}^2 \tag{2.15}$$

where $n_h m_h$ is the total diver stations sampled, m_h is the average diver stations sampled per primary unit, M_h is the total possible diver stations within a primary unit, and N_h is the total possible primary units in stratum h. We set M_h=226 for all strata, obtained by dividing the area of a primary unit (40,000 m^2) by the area of a diver station (177 m^2). Values of N_h were computed directly from the GIS digital habitat map.

The estimate of overall stratified mean density was obtained by

$$\overline{\overline{D}}_{st} = \sum_h w_h \overline{\overline{D}}_h \tag{2.16}$$

with stratum weighting factor w_h defined as

$$w_h = \frac{N_h M_h}{\sum_h N_h M_h} \tag{2.17}$$

The variance of $\overline{\overline{D}}_{st}$ was estimated by

$$\operatorname{var}\left[\overline{\overline{D}}_{st}\right] = \sum_h w_h^2 \operatorname{var}\left[\overline{\overline{D}}_h\right] \tag{2.18}$$

The standard error, $SE\left[\overline{\overline{D}}_{st}\right]$, is obtained by taking the square root of equation (2.18).Coefficient of variation (CV) of mean density was determined as the standard error expressed as a proportion of the mean,

$$CV\left[\overline{\overline{D}}_{st}\right] = \frac{SE\left[\overline{\overline{D}}_{st}\right]}{\overline{\overline{D}}_{st}} \tag{2.19}$$

Annual estimates of mean hogfish density and associated CVs are given in **Table 2.6c**. During the later survey years, hogfish densities have been estimated with progressively higher precision, a direct consequence of increases in both the number of primary units sampled (*n*) and total diver stations sampled (*nm*). On the other hand, we note that mean density from the RVC survey has generally increased over the last 5 years (i.e., 1997-2001).

2.6 Population Abundance Indices

Fishery-independent and fishery-dependent population abundance indices for hogfish are shown in **Figure 2.6**. Annual RVC survey mean densities for juvenile hogfish (length<199 mm) were fairly stable from 1989 to 1996, with the notable exception of a density increase in 1992 (**Figure 2.6a**). From 1996-2000, juvenile density appears to have undergone a substantial increase, leveling off in 2001. Exploited phase (legal size) hogfish densities from the RVC survey (**Figure 2.6b**) correspond to juvenile densities with a time lag of 1 to 2 years. This delay is not surprising since the age of first capture (t_c) is 2.75 years. An increase in exploited density in 1993 followed the increase in juvenile density in 1992. The sharp increase in exploited density in 2001 followed the increase in juvenile density during 1999 and 2000. There is also good correspondence between exploited hogfish density from the RVC survey and fishery-dependent CPUE (**Figure 2.6c**) for 1990 to 2001. A general increase from 1990 to 1993 followed by a decrease until 1999 is apparent in both indices of exploited stock abundance. In addition, both indices exhibit an increase from 2000 to 2001.

3.0 Fishery Stock Assessment

For the Florida hogfish stock assessment, we used a suite of age-structured, biomass-dynamic (which generally do not incorporate age-structure), and length-based (which include a probabilistic relationship between length dependent on age) population assessment models to allow estimation of initial population biomass and catchability between fleets that may change over time to evaluate trends in fishing mortality and population abundance. These three model classes remain the principal methodologies for fish stock assessments and the analysis of population dynamics. They are useful in cross-validation of results when they are applied in a complementary fashion to one another to provide other alternative views of the data, the population, and the status of the stock. In addition, when properly configured, these models allow estimation of several simultaneous (or sequential) fisheries fleets fishing on the same stock, and facilitate "tuning" of the model estimates to auxiliary population-dynamic indices as is often done in other age-structured and biomass-dynamic models (e.g., the CAGEAN model of Deriso et al. 1985; the ADAPT model of Gavaris 1988; and, the ASPIC model of Prager 1994). A overview of the fishery stock assessment process is shown in **Figure 3.1**. In this section, we use size-dependent means (average sizes) from both fishery-dependent and fishery-independent data, and fishery catch and effort data by fleet type, to estimate hogfish stock mortality rates through application of the aforementioned suite of stock assessment models.

3.1 Population Mortality and Abundance

Assessment of the status of the Florida hogfish stock required identification of robust population-dynamic variables that reflect the time-dependent relationship between trends in exploitation and stock size and productivity. A powerful indicator variable of population mortality is "average size" (in either length or weight) of animals in the exploited phase of the stock (Beverton and Holt 1957, Gulland 1983, Ault 1988, Ault and Ehrhardt 1991, Ehrhardt and Ault 1992, Ault et al. 1998, Quinn and Deriso 1999), here denoted as $\bar{L}$. *Average size* of the sampled population size distribution is written:

$$\bar{L}(t) = \frac{F(t)\int_{t_c}^{t_l} N(a,t)\, L(a,t)\, da}{F(t)\int_{t_c}^{t_l} N(a,t)\, da} \qquad (3.1)$$

where t_c is minimum age at first capture, t_λ is oldest age in the stock, $N(a,t)$ is abundance for age class a, $L(a,t)$ is length at age, and $F(t)$ is the instantaneous fishing mortality rate at time t integrated over all ages (sizes) in the fishable segment of the population abundance distribution.

The use of a "natural statistic" like $\bar{L}$ in stock assessment has deep roots in demographic theory and fisheries management (Beverton and Holt 1956, 1957, Ricker 1975). In general, it is well-known that $\bar{L}$ is highly correlated with average population size (both abundance and biomass), and so reflects the rate of fishing mortality operating in the fishery. As such, as fishing mortality rate increases, $\bar{L}$ decreases at a rate proportional to the stock's population-dynamic tolerance to perturbation. Average size is at its greatest when fishing mortality is lowest (i.e., near zero), and will continue to the point where, at relatively high exploitation rates, average size in the catch will be nearly equal to the minimum size of first capture regulated by the fishery. An interesting property of the estimator is that, with size-constant selectivity, $\bar{L}$ in the catch is exactly equal to $\bar{L}$ of the population remaining in the sea (Ault 1988, Ault et al. 1998). There exists a value of $\bar{L}$ corresponding to a unique population size that produces maximum sustainable yields on a continuing basis.

Using equation (3.1), we computed hogfish 'average lengths' from several data sources for the period 1978 to 2002: (1) RVC visual census (1980-2002); (2) MRFSS (1981-2001); (3) headboats (1978-1999); and, (4) BNP ramp intercept survey (1976-1998) databases. Abundance at size estimates by 1 cm intervals from the RVC survey are given in **Table 3.1**, and the observed size frequency distributions for a few representative years are shown in **Figure 3.2**. Comparisons of the of the average size estimates by various data sources are compared to the RVC data are given in **Figure 3.3**, where the estimates of the mean, variance, and 67% confidence interval followed Sokal and Rohlf (1969). We noted that the "average size" estimates for the several fishery-dependent surveys (MRFSS, headboat, and BNP) and the fishery-independent RVC survey had similar time trends. We also noted that the average size indices from the 4 independent data sets were highly correlated for the range of years (1991-1998) were data overlapped (MRFSS, headboats, RVC, BNP)

$$\begin{bmatrix} 1.0000 & 0.3191 & -0.5564 & 0.9147 \\ 0.3191 & 1.0000 & -0.6484 & 0.6011 \\ -0.5564 & -0.6484 & 1.0000 & -0.6034 \\ 0.9147 & 0.6011 & -0.6034 & 1.0000 \end{bmatrix}$$

(**Figure 3.4**). In general, the most reliable data for computing $\bar{L}$ came from the last decade (1991-2002), and an overall combined frequency distribution of these data rom the four sources for hogfish is given in **Figure 3.5**. Note that the mean of the combined 'average size' distribution from the 1991-2002 is about 340 mm FL, and the range of the distribution for the period is relatively compact. This is in comparison to an expected $\bar{L}$ of 488 mm FL for an unexploited resource The greater the correlation between the two independent estimates of $\bar{L}$, the more robust 'average length' should be as an indicator of stock status subject to exploitation. As a result, it is possible to compare these independent estimates since they each make unique estimates of the same population processes.

3.1.1 Estimation of F from Average Size Statistics

Persistent heavy fishing reduces the average fishable population size over time and imparts a uniquely distinguishing signature on population size structure, a characteristic that provides a unique and robust basis for population mortality estimation. We capitalized on this aspect of demographic theory to estimate the total instantaneous mortality rate *Z(t)* using our 5 sources of $\bar{L}(t)$ estimates using a reliable age-based algorithm applied to the average size of fish in the exploitable phase of the population (Ault and Ehrhardt 1991, Ehrhardt and Ault 1992, Ault et al. 1996, Ault et al. 1998):

$$\left[\frac{L_\infty - L_\lambda}{L_\infty - L_c}\right]^{\frac{Z(t)}{K}} = \frac{Z(t)\left(L_c - \bar{L}(t)\right) + K\left(L_\infty - \bar{L}(t)\right)}{Z(t)\left(L_\lambda - \bar{L}(t)\right) + K\left(L_\infty - \bar{L}(t)\right)} \tag{3.2}$$

where L_c is size at first capture, L_λ is maximum size in the stock, K and L_∞ are parameters of the von Bertalanffy growth equation, and t is year. While no explicit computational formula exists for analytical estimation of total mortality rate $Z(t)$, this estimate can be achieved fairly easily using an iterative numerical algorithm called LBAR given in Ault et al. (1996) and also found in the FAO FiSAT stock assessment library (FAO 2003). Equation (3.2) provides the means to produce unbiased estimates of total instantaneous population mortality rate $Z(t)$ (Ehrhardt and Ault 1992, Quinn and Deriso 1999). Justification for the use of the $\bar{L}$ statistic and mensuration formula (equation 3.2) centers around the notion that population mortality rates can be reliably estimated using any data source (i.e., either fishery-dependent and fishery-independent) and a with a bare minimum of population-dynamic parameters. Formal estimation of the instantaneous fishing mortality rate $F(t)$ is accomplished by subtracting the hypothesized rate of natural mortality M from the $\hat{Z}(t)$ estimate. The $\hat{Z}(t)$ statistic is robust to any population survey measure (i.e., RVC visual census, BNP creel, headboat or MRFSS survey data). Iterative application of the mortality estimation method using annual estimates of $\bar{L}$ provided time-series information on fishing mortality rates, and thus abundance, for the given time series.

The RVC time series of F estimates for the period 1980-2002 is given in **Figure 3.6**. Note the relative stability of the estimates since about 1990. A similar pattern was also noted for during this period for all the other data sources (**Figure 3.7a**). The median fishing mortality rate estimate for the distribution of F-estimates from all data sources for the 1990-1991 period was F=0.6123; however, the asymmetrical distribution was much better fit to a log-normal probability distribution with mean F=0.6940 with an offset parameter of 0.29 (**Figure 3.7b**). The 2001 estimate of $\hat{F}$ for hogfish obtained via the average size estimator assimilation exercise was F=0.5658**.**

3.2 Age-Structured Stock Synthesis Modeling

To examine fishery exploitation effects on the hogfish stock, we used a number of alternative age-structured and biomass dynamic assessment methodologies to compute independent estimates of catchability *q*, fishing mortality rate *F* and initial biomass B_0 from the fishery-dependent commercial and recreational catch-and-effort time series using continuous and age-structured stock synthesis models (c.f., **Tables 1.2, 2.5 and 3.1**). The stock synthesis modeling procedure employs a general population derivative to express stock response to exploitation, and then uses maximum likelihood principles (e.g., Haddon 2001) to provide robust statistical predictions of catches by fleets, annual population abundance, and fleet-specific fishing mortality rates. The mathematics of the general model detail the rate of change in population abundance of an age *a* fish with respect to time

$$\frac{dN(a)}{dt} = R - ZN(a) = R - (F + M)N(a) \qquad (3.3)$$

At equilibrium the population size N_{eq} is

$$N_{eq} = \frac{R}{Z} \qquad (3.4)$$

Recruitment to the exploitable phase, since was zero during in preceding life stages, is

$$R_{t_c} = R_o e^{-Z} = R_o e^{-M} \qquad (3.5)$$

The average number alive during any time *t* is written

$$\overline{N}_t = \frac{R_t}{Z_t} + \left(\frac{N_t - R_t}{Z_t}\right)e^{-Zt} \qquad (3.6)$$

Thus, catch during the interval *t* is

$$C_t = F_t \overline{N_t} = F_t\left[\frac{R_t}{Z} + \left(\frac{N_t - R_t}{Z}\right)\left(1 - e^{-Z}\right)\right] = \frac{F_t}{Z}\left[R_t + (N_t - R_t)(1 - e^{-Z})\right] \qquad (3.7)$$

So that average population abundance during that interval can be generally estimated as

$$\overline{N_t} = \frac{C_t}{F_t} \tag{3.8}$$

Thus, catch in year $t+1$ is

$$C_{t+1} = F_{t+1}\frac{C_t}{F_t} \tag{3.9}$$

Total instantaneous fishing mortality, F_t, for the fishery can be partitioned into component sector mortalities in terms of units of nominal fishing effort f_j for each fishery sector j (e.g., recreational and commercial) multiplied times stock catchability (proportion of stock removed per unit of nominal fishing effort) for that gear. These components are additive in the rate function

$$F_t = \left(q_{\mathrm{Re}cr}\, f_{\mathrm{Re}cr,t} + q_{Comm}\, f_{Comm,t}\right) \tag{3.10}$$

In the algorithm the model endeavors to provide estimates of catchability q_j for each fleet type and total population abundance at the beginning of the interval N_o, given fleet-specific inputs of f_t, C_t and stock-wide M. Predicted total catch for the time period $t+1$ can be calculated as

$$\hat{C}_{t+1} = \frac{F_{t+1}}{Z_t}\left(R_t + (N_t - R_t)\left(1 - e^{-(M+qf_t)}\right)\right) \tag{3.11}$$

which can be rewritten as

$$\hat{C}_{t+1} = \frac{Z_t - M}{Z_t}\left[R_t + (C_t - N_{eq})(1 - e^{-Zt})\right] \tag{3.12}$$

So, more generally the time series of predicted catches may be expressed as

$$\begin{aligned} \hat{C}_{t+2} &= F_{t+2}\frac{\hat{C}_{t+1}}{F_{t+1}} \\ &\vdots \\ \hat{C}_{t+l} &= F_{t+l}\frac{\hat{C}_{t+l-1}}{F_{t+l-1}} \end{aligned} \tag{3.13}$$

The actual statistical fitting process used a given time series of catches C_t and nominal fishing effort f_t and initial estimates of initial population size N_o and recruitment R_t. The stock synthesis model produces a vector of expected population abundance for each year *t*. The model estimates the catchability q_j coefficient for each fleet type *j* and then predicts the catches for each fleet sector as

$$\hat{C}_{jt} = \frac{\hat{C}_t q_j f_{jt}}{Z_t - M} \tag{3.14}$$

The model varies the values of initial population size and each year's recruitment until the difference between the observed catches C_t and predicted catches $\hat{C}_t$ are minimized according to a least squares criterion of fit using normal random residual errors between the observed and predicted catches written as

$$\min \sum \left(C_t - \hat{C}_t \right)^2 \tag{3.15}$$

This relationship can be represented by a simplification of the maximum likelihood estimator for log-normal random errors (Haddon 2001) which log-transforms both the observed and predicted catches to normalize the distribution of residual errors. Estimates of model parameters are obtained by maximizing the log-likelihood (LL) function

$$LL(data|b_0, b_1, \ldots, b_n) = \sqrt{\frac{1}{2p\,\hat{s}}} \prod_t^n e^{\frac{-(\ln C_t - \ln \hat{C}_t)^2}{2\hat{s}^2}} \tag{3.16}$$

written generally as

$$LL = -\frac{n}{2}\left[\ln(2p) + 2\ln(\hat{s}) + 1\right] \tag{3.17}$$

Setting the objective function to minimize the differences between observed and predicted catches for the fleets results in a log-likelihood (LL) function that incorporated inter-calibrated fishery-dependent data sets of both recreational and commercial catches and nominal fishing effort for the period 1982 to 2001

$$LL = Max\left[\frac{-n^2}{2}\left(\sum_{t=1}^{n}\left[\ln C_t - \ln \hat{C}_t\right]^2\right)\right] \qquad (3.18)$$

where n is the number of observed catches. Commercial data for commercial catch and effort were not available for the years 1982-1984, but we used the most recent years as an approximate value.

We further explored the estimation process using progressively more sophisticated and structured population models, and complex multi-objective likelihood functions. We configured the complex age-structured stock synthesis model to fit to both recreational and commercial catch-and-effort data, but also “tuned” this model to the RVC fishery-independent data for juveniles (J), exploited adults (E), recruitment variation, and *a priori* knowledge of the most recent year’s fishing mortality estimate. In this case, the model log-likelihood (LL) function took the general form

$$LL = Max[\frac{-n^2}{2}(\sum_{t=1}^{n}(\ln R_t - \hat{R})^2 + \sum_{t=1}^{n}(\ln C_t - \hat{C})^2 + \sum_{t=1}^{n}(\ln Z_t - \hat{Z})^2 + \sum_{t=1}^{n}(\ln \overline{L_t} - \hat{\overline{L}}_t)^2 + \sum_{t=1}^{n}(\ln J_t - \hat{J})^2 + \sum_{t=1}^{n}(\ln E_t - \hat{E})^2)] \qquad (3.19)$$

Some examples of “tuned” predicted fits to the distribution of observed RVC survey juvenile and exploited phase indices are shown (**Figure 3.8a**), as well as stock synthesis model predicted average sizes in comparison to those observed in the RVC survey (**Figure 3.8b**). In addition, the model predicted fits relative to the observed recreational and commercial catch data are shown in **Figure 3.9**. The predicted catches appeared to be relatively close to those observed.

3.3 Surplus Production Models

For completeness, we employed non-equilibrium ASPIC (Prager 1994) and equilibrium PRODFIT (Fox 1975) surplus production models and fit them to fishery-dependent catch-and-effort data. The generalized stock production model is

$$dB/dt = HB_t^{m} - KB_t - qf_tB_t \qquad (3.20)$$

where, B is the population biomass (usually in terms of weight), f is effective effort, i.e., standardized from nominal fishing effort and calibrated to be proportional to the instantaneous fishing mortality coefficient. The parameter q is the catchability coefficient, and H, K, and m are constant parameters. At equilibrium (i.e., dB/dt = 0), then it follows that

$$B^{m-1} = (K/H) + (q/H)f$$

and,

$$U^{m-1} = (Kq^{m-1}/H) + (q^m/H)f.$$

So, the expected CPUE for a given f is

$$U = (a + bf)^{\frac{1}{m-1}} \tag{3.21}$$

where U is the catch per unit effort as a function of f given the underlying population production dynamics. The management performance statistics of the model are:

$U_{max} = a^{\frac{1}{m-1}}$; maximum (at low to no exploitation) catch rates.

$U_{msy} = (a/m)^{\frac{1}{m-1}}$; optimum catch rates (corresponds with MSY rate)

$f_{msy} = (a/b)(1/m-1)$; fishing mortality rate necessary to achieve U_{msy}.

$MSY = (a/b)(1/m-1)(a/m)^{\frac{1}{m-1}}$; yield in weight obtained at U_{msy};

where U_{max} is the relative density of the population before exploitation; U_{msy} is the relative population density providing the maximum sustainable yield; f_{msy} is the amount of fishing effort to obtain the maximum sustainable yield; and MSY is the maximum sustainable yield. Surplus production P_h during the time interval is

$$P_h = B_{t+d} - B_t + Y_t \tag{3.22}$$

The log-likelihood function of the surplus production model catches Y_t can be obtained as

$$LL = Max\left[\frac{-n^2}{2}\left(\sum_{t=1}^{n}\left[\ln Y_t - \ln \hat{Y}_t\right]^2\right)\right] \qquad (3.23)$$

3.4 Summary of Fishing Mortality Estimates

The resultant comparisons of all dynamic model estimates of fishing mortality rate *F* for the various data sets are shown in **Figure 3.10**. In general, the cross validation exercise showed that all the age-structured stock synthesis and biomass-dynamic methodologies produced *F* estimates that were relatively in good agreement with those length-based F estimates derived from RVC average size statistics using the LBAR model. Overall, the variance of fishing mortality estimates was greatest for in the earliest years of the data, a situation most likely due to greater imprecision in sampling survey designs in the early years of data collection. For example, the RVC produced the highest F estimates during 1986-1989, a period when the surveys were focused on Biscayne National Park an area of highest regional fishing intensity (Ault et al. 2001). Fishing mortality estimates were relatively coherent during the last 5 to 10 year period. In the times series, F peaked during the mid- to late-1980s, then slowly declined through the 1990s (**Figure 3.11a**), a trend evident in all the time series. The current (2001) “best” fishing mortality estimate was F=0.56. The preliminary 2002 F was 0.5 as determined from the RVC survey database. During the past two decades, the proportion of F due to recreational fishing rose from about 80% of the total fishing mortality in the early 1980s, to more than 90% of total F in the last decade (**Figure 3.11b**).

4.0 Fishery Risk Assessment

Since hogfish are highly esteemed as food fish (Gomon 1978), a relatively long history of intensive fishing pressure has reduced many populations worldwide to critically low levels. Consequently, the species has been identified as vulnerable to extinction (e.g., IUCN 2000). Declines in catches, catch rates, and average sizes in the catches of Florida hogfish has raised a growing concern regarding the sustainability of the fishery. Unfortunately, basic fishery-dependent data required to conduct a full stock assessment on the status of the Florida hogfish stock has only been collected since the early 1980s. At the same time, to stem the observed declines in Florida hogfish catches, the fishery had specific size- and bag limit regulations implemented in 1993 (www.gulfcouncil.org; www.safmc.org)..

4.1 Fishermen Compliance with Regulations

Current regulations by FWC Marine Fisheries Commission impose a 12 inch minimum size limit for both commercial and recreational fisheries; and, a 5 fish bag limit per day for the recreational fishery. To evaluate compliance with these regulations for the time series of available data, we assumed that the laws were in effect for the entire 1980-2001 time period (**Table 4.1**). This analysis shows that prior to 1993, about 20% of all catches contained fish below the 12 inch minimum, but that has been reduced to about 5% of all catches since 1993. In terms of bag limits, approximately 10% of all catches exceeded the five fish per day limit prior to 1993, and this has reduced to about 3-5% since the 1993 imposition of the regulations by the Florida FMC.

4.2 Age-Structured Analytical Yield Modeling

Our analyses have established that the fishing mortality rate for Florida hogfish has ranged from about 0.4 to 0.8 over the last decade, with the most likely current estimate of *F* being 0.50 (**Figure 4.1**). To assess the consequences of the observed exploitation history, in this section we use these estimates in a age-structured analytical yield simulation model to evaluate population productivity using key management benchmarks, to assess the fishery relative to national standards for sustainability on an annual basis for the past 20 or so years, and to address the prospects for sustainability of this important Florida fishery resource.

We used the computer simulation model, REEFS (**R**eef-fish **E**xploitation **E**ffects **F**ishery **S**imulator, Ault et al. 1998), that employs a stochastic size-dependent-on-age algorithm to determine the expected population age-size distribution for all population cohorts for a continuous life extending from egg, early larval stages, to juveniles, to maturity and through the exploited life span to maximum size-age (**Figure 4.2**). The REEFS model links and integrates a number of intrinsic demographic functions that define hogfish birth, growth and survivorship processes, including selection and extraction by the fishery. The REEFS population simulation model describes the dynamic progression of ensemble numbers of fish at lengths following Ault and Rothschild (1991), and Ault et al. (1998)

$$N(L|a,t) = \int_{t_r}^{t_l} R(g-a)S(a)q(a)p(L|a)da \qquad (4.1)$$

where $R(\gamma\text{-}a)$ is cohort recruitment date lagged back to birth date, $S(a)$ is survivorship to age a, $\Theta(a)$ is sex class fraction at age a to account for hermaphroditic (i.e., protogynous or protandric) life histories common to tropical groupers and snappers, and $p(L|a)$ is the probability of being length L given the fish is age a (Ault 1988, Ault and Rothschild 1991, Ault and Olson (1996), Ault et al. 1997, 1998). The modeled fishing mortality rate of recreational and commercial fishers (is equivalent to the ‘viewing power’ of SCUBA divers that were assumed to remove (or sight) fish with a ‘knife-edged selectivity pattern’ over the range of exploitable sizes (e.g., Gulland, 1983). This confers that all exploited sizes (ages) of fish are selected with equal probability

$$F(t) = \begin{cases} 0 & if \quad L|a < L_c \\ \hat{F}(t) & if \quad L|a \geq L_c \end{cases} \qquad (4.2)$$

where the size of first capture L_c is that regulated by regional fishery management (i.e., 304.8 mm TL for hogfish). Along with the estimated instantaneous rate of fishing mortality, species-specific population dynamics parameters were also used as model inputs (**Table 1.2**).

4.3 Biological Reference Points

The Florida hogfish fishery is currently experiencing relatively high levels of fishing mortality (i.e., high exploitation rates) which appear to have had significant impacts on the stock over the last several decades. For this section's analyses, we configured the REEFS model to validate the average size-F estimates we obtained earlier, and to assess several biological reference points important to fishery management. The most relevant contemporaneous fishery management benchmarks include: yield-per-recruit (YPR); spawning potential ratio (SPR); and, the current and historical stock biomass-fishing mortality rate ratios which form the "limit control rules" of the precautionary approach to fishery management (Restrepo et al. 1998, Restrepo and Powers 1999).

4.3.1 Population Biomass and Yield-per-Recruit (YPR)

We used the REEFS model and estimates of fishing mortality rates to determine the population biomass *B(a,t)*, computed as the product of numbers-at-age times weight-at-age, and fishery lifetime yield in weight Y_w for hogfish

$$Y_w(F, L_c, t) = F(t)\int_{L_c}^{L_l} B(L|a,t)dL = F(t)\int_{L_c}^{L_l} N(L|a,t)W(L|a,t)dL \qquad (4.3)$$

Yield-per-recruit (YPR), or the lifetime yield expected from a single recruited individual, was then calculated by scaling yield to average recruitment.

4.3.2 Spawning Potential Ratio (SPR)

We also used the REEFS model to determine mature or spawning stock biomass for each year t (*SSB(t)*) to provide a quantitative measure of the stock's reproductive potential or capacity to produce newborn, ultimately realized at the population level as successful cohorts or year classes. Spawning stock biomass is obtained by integrating over individuals in the population between the minimum size of first maturity (L_m) and maximum reproductive size (here assumed to be the maximum size L_λ)

$$SSB(t) = \int_{L_c}^{L_1} B(L|a,t)dL \tag{4.4}$$

Spawning potential ratio at time *t* , i.e., *SPR(t)*, is a contemporaneous management reference point that measures the stock's potential capacity to produce optimum yields on a sustainable basis. SPR(t) is the fraction expressed as the ratio of current exploited spawning stock biomass *SSB(t)* relative to the equilibrium unexploited *SSB(0)*

$$SPR(t) = \frac{SSB(t)}{SSB(0)} \tag{4.5}$$

SSB(0) is the mature population biomass in the sea with no exploitation. Thus, resultant estimated SPRs are then compared to the U.S. Federal standards which define 30% SPR as the "overfishing" threshold at which the stock is no longer sustainable at current exploitation levels (Rosenberg et al. 1996). Generally high and increasing exploitation rates over time successively eliminates older, more fecund size classes through a process known as "juvenescence", ultimately producing an overall younger stock size-age distribution (Ricker 1963, Ault 1988, Ault and Olson 1996, Ault et al. 1998). This fact is extremely important in the context of stock and recruitment, since the fecundity potential of individuals increases exponentially with size. Such a phenomenon will be reflected by reductions of the stock's spawning capacity, which itself is related to the expectation of new recruits to sustain the population over the longer run.

4.4 Status of the Florida Hogfish Stock

The REEFS-based analysis of YPR and SPR for hogfish is shown in **Table 4.2**. For hogfish, the rate of mortality that produces "maximum sustainable yield" is about Fmsy=0.13. This estimate is very close to the one derived from stock synthesis modeling (**Figure 4.3**). Fishing at F_{msy} reduces the spawning potential ratio (the proportion of the virgin spawning biomass available) to about 34.6% of the unexploited spawning population size. At $F_{0.1}$ SPR is about 38.1%. Remarkably, the current estimated rate of fishing mortality of F=0.566 for 2001 in Florida has reduced the spawning potential ratio to less than 9% of its historical maximum and has a YPR=0.48

kg per recruit lifetime yield. The YPR analysis shows that the current fishing mortality rate and regulated age-of-first-capture (t_c) put the hogfish stock well below the eumetric line in the growth- and recruitment-overfishing zone of the YPR graph (**Figure 4.4** and **Figure 4.5**). According to our estimates, the hogfish stock is currently both growth-overfished (which requires that L_c be increased) and recruitment-overfished (which requires a substantial decrease in F). All indications are that this fishery has been overfished for more than a decade. From the perspective of ecological theory, we believe this is an ominous result in terms of hogfish population stability and resilience for the longer run. If the fishery were to remain at current level of F=0.566, fishery management should strive to increase L_c to 524 mm FL (20.6 in) which would increase the YPR by 88.4%. This would also result in an increase in SPR to 39.8%, well above the Federal standard. If management were to optimize with respect to both F and L_c (i.e., L_c=456 mm FL, 18"; F_{msy}=0.13025), this would produce an 51.7% increase in YPR and put stock SPR at 55%.

The YPR and SPR biological reference points are relatively robust biological measures of potential fishery yields and population recruitment, respectively (Caddy and Mahon 1995). As such, they help to focus on biological (size) and fishing (intensity) controls for managing current and future fishery production. Taken together, these management benchmarks characterize the status of stocks under exploitation relative to Federal and International fishery management standards. Thus, these analyses provide the theoretical and quantitative basis for the assessment of the hogfish population, and indicate the efficacy of current fishery management practices and their sufficiency to provide sustainable fisheries now and into the future.

4.5 Benchmarks for a Sustainable Fishery

The Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) contains a set of National Standards for fishery conservation and management, the first of which states:

> *"Conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimum yield from each fishery for the United States fishing industry."*

The MSFCMA also required the Secretary of Commerce to "establish advisory guidelines (which shall not have the force and effect of law), based on the national standards, to assist in the development of fishery management plans". These national standard guidelines (NSGs) were published as a final rule in May 1998. Following the NSGs, Technical Guidelines were developed (Restrepo et al. 1999, Restrepo and Powers 1998) to translate the NSGs into criteria so that scientific advice could be offered to regional Fishery Management Councils to assist in implementing the MSFMCA. Key points arising were that:

(1) Maximum sustainable yield (*MSY* threshold) is to be viewed as a limit **NOT** to be exceeded;

(2) Two measures determine a fish stock's management status: (a) the current level of fishing mortality relative to the rate that produces MSY (denoted as F/F_{msy}); and, (b) the current amount of stock spawning biomass relative to the spawning biomass at MSY (denoted as B/B_{msy});

(3) There should be maximum standards of fishing mortality rates which should not be exceeded, called Maximum Fishing Mortality Threshold (MFMT); there should be a Minimum Stock Size Threshold (MSST) under which a stock's spawning biomass would be considered as depleted; and, these criteria and measures should be linked together through "control rules" which specify actions to be taken (i.e., changes in management measures to alter fishing mortality rates) depending upon the status of current spawning biomass relative to B_{msy} and MSST and the status of the fishing mortality rate relative to F_{msy} and MFMT.

To address these emerging fishery management benchmark criteria for the Florida hogfish fishery, we conducted new analyses that established fishery limit control rules consistent with the "precautionary approach". Criteria used to set target catch levels as explained above are explicitly *risk averse*. A risk averse precautionary approach would set OY (optimum yield) below MSY as a function of uncertainty. Thus, the greater the uncertainty, the greater the distance between the two. The *precautionary approach* to fisheries management requires avoidance of overfishing, restoration of already overfished stocks, explicit specification of management objectives including operational targets and constraints (e.g., target and limit reference points), taking account of uncertainty by being more conservative, and avoidance of excess harvest capacity. In addition, this approach requires formulation of decision rules that stipulate in advance what actions will be taken to prevent overfishing and promote stock rebuilding.

Limit control reference points are designed to constrain exploitation within safe biological limits so that stocks retain the ability to produce maximum sustainable yield. Overfishing is a level or rate of fishing mortality that jeopardizes the long-term capacity of a stock or stock complex to produce MSY on a continuing basis. In this arrangement, the fishing mortality rate which generates MSY should be regarded as the minimum standard for limit reference points. The limit MSST (minimum stock size threshold) is used to decide what level of fishing mortality indicates "overfishing", and when the stock is in an "overfished" condition. If spawning biomass drops below MSST, then the regional fishery management councils are mandated to take remedial actions to end overfishing and rebuild overfished stocks to MSY levels relatively rapidly (i.e., generally in less than 10 years).

When all the available data are used to compute the mortality rates and stock biomass levels in terms of the limit control rule theory, the resulting plot indicates that every estimate for each year from every data type indicates serious overfishing is occurring on the Florida hogfish stock (**Figure 4.6**). When the individual components of the limit control rule are examined (**Figure 4.7**), these results indicate that the current levels of fishing mortality is more than 4 times the level that produces maximum sustainable yield, and further, that stock spawning biomass is at critically low levels. Using the intrinsic rate of increase estimated using ASPIC non-equilibrium surplus production modeling, we conducted a forward projection analysis of the hogfish stock using three scenarios: (1) recovery when F set to 0; (2) maintaining the current level of F indefinitely into the future; and, (3) decreasing F to its MSY level (**Figure 4.8**). In each of the scenarios it would take more than 20 years to rebuild the stock to MSY levels, a recovery time horizon that is about twice as long as what is mandated by National Standard 1 for sustainable fisheries. It is apparent that leaving F at the current rate would only lead to further diminutions of the resource, and perhaps fishery collapse. Thus, the results presented in this stock assessment report suggest that immediate and decisive fishery management intervention is required at this time to begin the process of stock recovery to at least the minimum Federal standards for fishery sustainability.

4.6 Research and Data Needs

We found a high degree of agreement between the fishery-independent age-based average size estimation indicators of fishing mortality rate and those derived from stock synthesis and biomass-dynamic models of fishery-dependent and fishery-independent data (i.e., past 5-year average F=0.57). These results suggest that the Florida hogfish stock is seriously overfished at present according to Federal standards for sustainability. As a result, the current levels of reproductive stock biomass are at critically low levels (about 9% of the unfished level), and the fishery may be in danger of collapse and loss of economic and ecological productivity. Due to the relatively short time series and relatively low contrasts of CPUE for the available fishery data, the absolute historical limits of stock size and productivity are still somewhat unclear. This would suggest the need for further assessment analyses using other classes of modeling procedures like stock reduction analyses (Kimura et al. 1984), that could allow the merging of quantitative data time series with observations and opinions about historical states of the fishery.

Nonetheless, the analyses presented here suggest that minimal first and immediate management action should be to raise the minimum size limit to about 20 inches FL to eliminate the growth overfishing that is presently occurring in the fishery. A larger size limit could be very effective if compliance was good, and would likely increase the population egg production at spawning as this would serve to protect a broader size range of the female stock component.

Another obvious need is to reduce the rate of total fishing mortality be waged on the stock by recreational and commercial fishery sectors. Our recent estimates of fishing mortality rate suggest that the recreational fishery has generated between 85 and 95% of the total since the 1980s. Although the recreational fishery may not have been the principal source of fishing mortality that caused stock biomass levels to dip below sustainable levels, at present the principal source of fishing mortality is clearly coming from recreational anglers. In fact, we estimate that spear fishers (both recreational and commercial) are the major sources of hogfish fishing mortality. Hence, a recommendation would be to either restrict this sector to fishing in particular areas by perhaps limiting the use of SCUBA with spearfishing (this could provide some depth protection), establish smaller bag limits (e.g., 1 fish), and/ or limit the amount of time during a year that spear fishing gears may be used.

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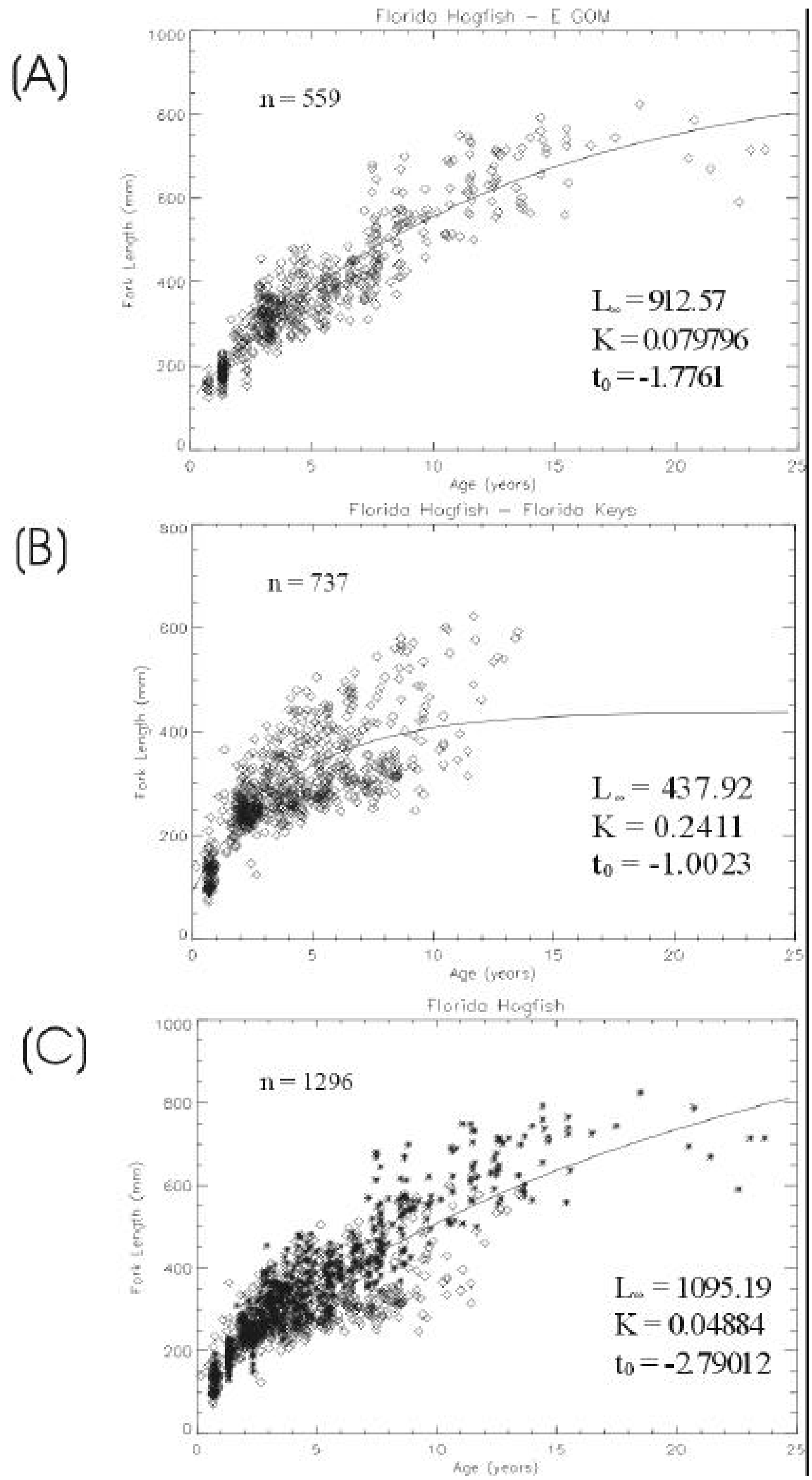

Figure 1.1.- Growth of the hogfish as expressed by the von Bertalanffy fork length dependent on age function estimated from the data of McBride (2001). (A) eastern Gulf of Mexico; (B) Florida Keys (east coast); and, (C) combined Gulf of Mexico (asterisks) and Florida Keys (diamonds) data.

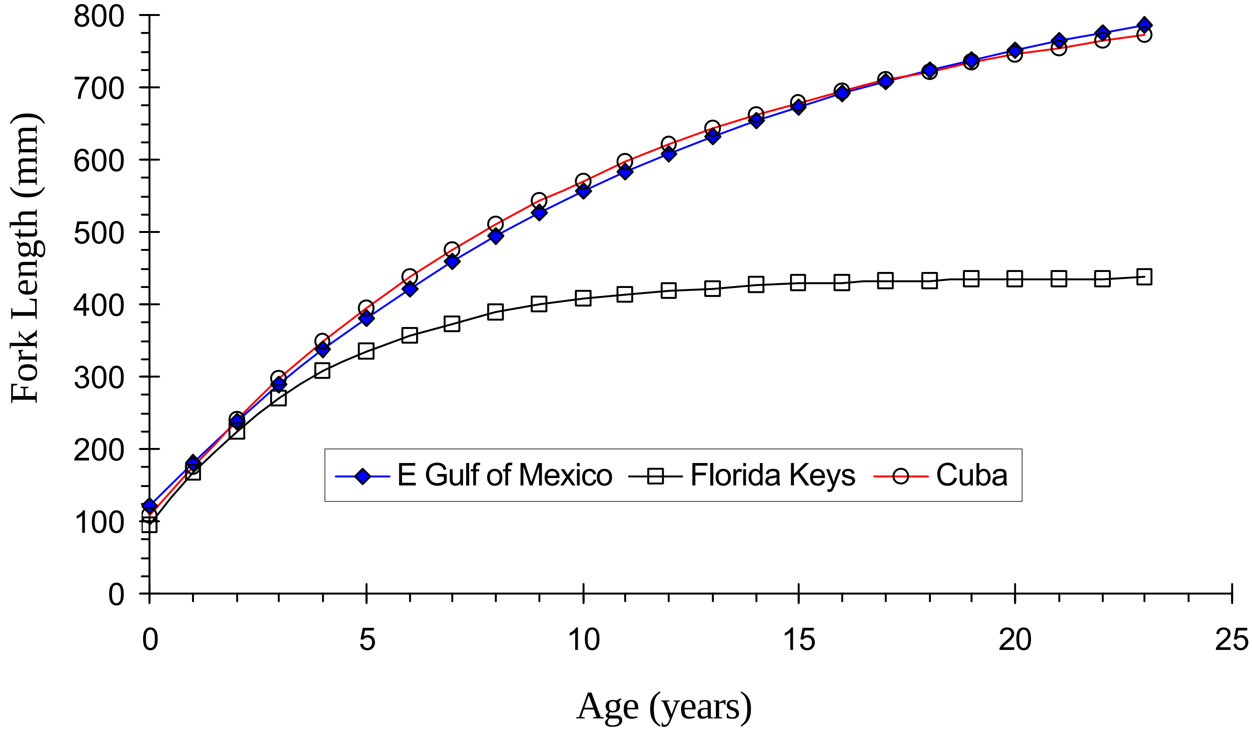

Figure 1.2.- Graphical comparison between hogfish von Bertalanffy growth models of fork length (mm) on age (yr) at 3 locations. Gulf of Mexico and Florida Keys curves fitted from the data of McBride (2001). Cuban growth curve from Claro et al. (2002).

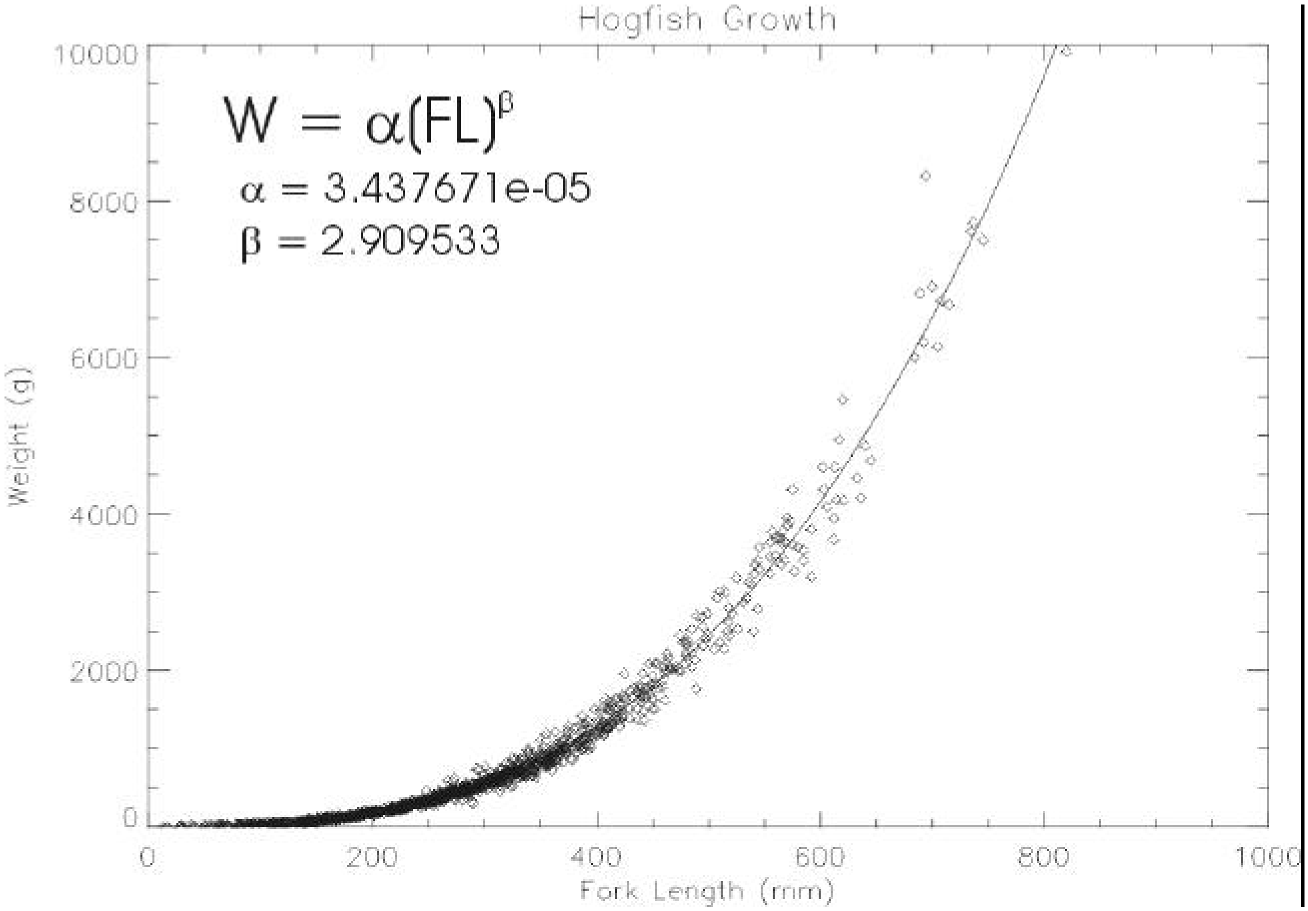

Figure 1.3.- Allometric relationship between hogfish weight (g) dependent on fork length (mm). Data from McBride (2001).

	GoM	FL Keys	Cuba
(A) L_inf	912.57	437.92	850.00
W_inf	14101.2	1665.3	11468.5
K	0.0798	0.2411	0.0980
t_0	-1.78	-1.00	-1.38
a	3.438e-05		
b	2.9095		

(B)

	FL GoM		FL Keys		Cuba		GoM	
Age (yr)	FL (mm)	FL (in)	FL (mm)	FL (in)	FL (mm)	FL (in)	W (kg)	W (lbs)
0	120.6	4.7	94.0	3.7	107.5	4.2	0.04	0.09
1	181.3	7.1	167.7	6.6	176.8	7.0	0.13	0.28
2	237.4	9.3	225.6	8.9	239.7	9.4	0.28	0.62
3	289.2	11.4	271.1	10.7	296.6	11.7	0.50	1.10
4	337.0	13.3	306.8	12.1	348.3	13.7	0.78	1.71
5	381.1	15.0	334.9	13.2	395.1	15.6	1.11	2.45
6	421.9	16.6	357.0	14.1	437.6	17.2	1.49	3.29
7	459.5	18.1	374.3	14.7	476.1	18.7	1.92	4.22
8	494.3	19.5	387.9	15.3	511.0	20.1	2.37	5.22
9	526.4	20.7	398.6	15.7	542.6	21.4	2.84	6.27
10	556.0	21.9	407.1	16.0	571.3	22.5	3.34	7.35
11	583.3	23.0	413.7	16.3	597.4	23.5	3.84	8.46
12	608.6	24.0	418.9	16.5	620.9	24.4	4.34	9.56
13	631.9	24.9	422.9	16.7	642.3	25.3	4.84	10.67
14	653.4	25.7	426.2	16.8	661.7	26.1	5.34	11.76
15	673.3	26.5	428.7	16.9	679.3	26.7	5.82	12.83
16	691.6	27.2	430.7	17.0	695.2	27.4	6.30	13.88
17	708.6	27.9	432.2	17.0	709.7	27.9	6.75	14.89
18	724.2	28.5	433.4	17.1	722.8	28.5	7.20	15.87
19	738.7	29.1	434.4	17.1	734.6	28.9	7.62	16.81
20	752.0	29.6	435.2	17.1	745.4	29.3	8.03	17.70
21	764.3	30.1	435.7	17.2	755.2	29.7	8.42	18.56
22	775.7	30.5	436.2	17.2	764.0	30.1	8.79	19.38
23	786.2	31.0	436.6	17.2	772.1	30.4	9.14	20.15

Table 1.1.- (A) Parameters for length-age and weight-age growth models for hogfish by geographical region. (B) Relationship between age, length and weight for hogfish in Florida and Cuba.

Table 1.2a - Key population-dynamic rate parameters for hogfish (*Lachnolaimus maximus*) in the Florida coral reef ecosystem. Length units in terms of fork lengths.

Model Paramaters	Definition	Value	Units	Source
t_{l}	Oldest (largest) age in population	23	years	McBride (2001)
M	Natural mortality rate	0.13025	$year^{-1}$	This paper
L_{l}	Largest (oldest) size in length in population	786.20	mm	This paper
$L_{\text{¥}}$	Ultimate length	912.57	mm	This paper
W_{l}	Largest (oldest) size in weight	9.314	kg	This paper
$W_{\text{¥}}$	Ultimate weight	14.10	kg	This paper
K	Brody growth coefficient	0.0798	dimensionless	This paper
t_0	Age at which size equals 0	-1.776	years	This paper
L_m	Minimun size of maturity	165.6	mm	McBride (2001)
t_m	Minimum age of maturity	0.67	years	This paper
L_c	Minimum size of first capture	275.5	mm	FFWCC/MFC
t_c	Minimum age of first capture	2.727689	years	This paper
a_{WL}	Scalar coefficient of weight on length	3.437671e-05	dimensionless	This paper
b_{WL}	Power coefficient of weight on length	2.909533	dimensionless	This paper

Table 1.2a.1- Glossary of model parameter definitions and units for life table variables common to mortality estimation (e.g., LBAR, ASPIC, ADAPT and stock synthesis) and reef fish length-based fishery simulation model (REEFS) used in Florida hogfish stock assessment risk analysis.

Parameter	Definition	Units
t_r	Age of recruitment	months
L_r	Size at recruitment	mm
t_m	Minimum age of maturity	months
L_m	Minimum size of maturity	mm
t_c	Minimum age of first capture	months
L_c	Minimum size of first capture	mm
t_λ	Oldest (largest) age	years
L_λ	Largest (oldest) size	mm
W_∞	Ultimate weight	kg
L_∞	Ultimate length	mm
K	Brody growth coefficient	$year^{-1}$
t_0	Age at which size equals 0	years
α_{WL}	Scalar coefficient of weight on length	dimensionless
$ß_{WL}$	Power coefficient of weight on length	dimensionless
Θ(a)	Sex ratio at age *a*	dimensionless
q_j	catchability coefficient for fleet j	dimensionless
Variable		
W(a,t)	Weight at age *a* at time *t*	g
L(a,t)	Length at age *a* at time *t*	mm
N(a,t)	Numbers at age *a* at time *t*	number of fish
M(a,t)	Natural mortality rate at age *a* at time *t*	$year^{-1}$
$\bar{L}(t)$	Average size in exploited phase for stock *s*	mm
F(a,t)	Fishing mortality rate at age *a* at time *t*	$year^{-1}$
S(a)	Survivorship to age *a*	dimensionless
Z(t)	Total mortality rate in year *t*	dimensionless
B(a,t)	Biomass at age *a* in year *t*	kg
C(t)	catch	number of fish
$Y_w(t)$	Yield in weight in year t	mt
SSB(t)	Spawning stock biomass in year *t*	mt
SPR(t)	Spawning potential ratio in year *t*	dimensionless
B_0	Stock spawning biomass at zero exploitation	mt
B_{msy}	Stock spawning biomass at MSY	mt
R	recruitment of new individuals	number of fish
N_o	initial population size	number of fish

Table 1.2b - Key population-dynamic rate parameters at age used in hogfish age-structured stock synthesis modeling.

Age	1	2	3	4	5	6	7	8	9	10
Lorenzen Surv	0.3027	0.4831	0.5848	0.6490	0.6930	0.7249	0.7490	0.7678	0.7828	0.7951
survivorship	1.000000	0.302717	0.146247	0.083333	0.044423	0.020106	0.008097	0.003074	0.001139	0.000419
Length	118.28	170.70	219.08	263.74	304.97	343.03	378.17	410.60	440.54	468.17
Fecundity	5169	15821	33867	59641	92882	132956	179006	230068	285155	343302
Weight	0.0172	0.0499	0.1029	0.1764	0.2689	0.3784	0.5022	0.6378	0.7824	0.9335
Proportion female	0.9656	0.9445	0.9149	0.8754	0.8259	0.7675	0.7027	0.6344	0.5662	0.5008
Proportion mature	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Vulnerability	2.5600e-06	6.5493e-04	1.6519e-02	1.4367e-01	5.0000e-01	8.1131e-01	9.3654e-01	9.7725e-01	9.9101e-01	9.9611e-01
NatSurvship	1.000000	0.302717	0.146256	0.085525	0.055506	0.038465	0.027884	0.020885	0.016036	0.012553
Eggs	4991	14943	30984	52207	76710	102048	125779	145959	161443	171916

Age	11	12	13	14	15	16	17	18	19	20+
Lorenzen Surv	0.8052	0.8137	0.8210	0.8271	0.8325	0.8371	0.8412	0.8448	0.8480	0.8480
survivorship	1.54e-04	5.68e-05	2.11e-05	7.86e-06	2.95e-06	1.11e-06	4.19e-07	1.59e-07	6.07e-08	2.32e-08
Length	493.69	517.24	538.98	559.04	577.57	594.67	610.46	625.03	638.48	650.90
Fecundity	403608	465250	527500	589721	651373	712000	771232	828770	884383	937897
Weight	1.0890	1.2468	1.4051	1.5625	1.7176	1.8694	2.0172	2.1602	2.2980	2.4302
Proportion female	0.4403	0.3860	0.3383	0.2969	0.2615	0.2313	0.2056	0.1839	0.1654	0.1498
Proportion mature	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Vulnerability	9.9818e-01	9.9909e-01	9.9952e-01	9.9974e-01	9.9985e-01	9.9991e-01	9.9994e-01	9.9996e-01	9.9998e-01	9.9998e-01
NatSurvship	0.009981	0.008037	0.006540	0.005369	0.004441	0.003697	0.003095	0.002604	0.002199	0.012267
Eggs	177724	179605	178444	175100	170311	164662	158590	152405	146317	140461

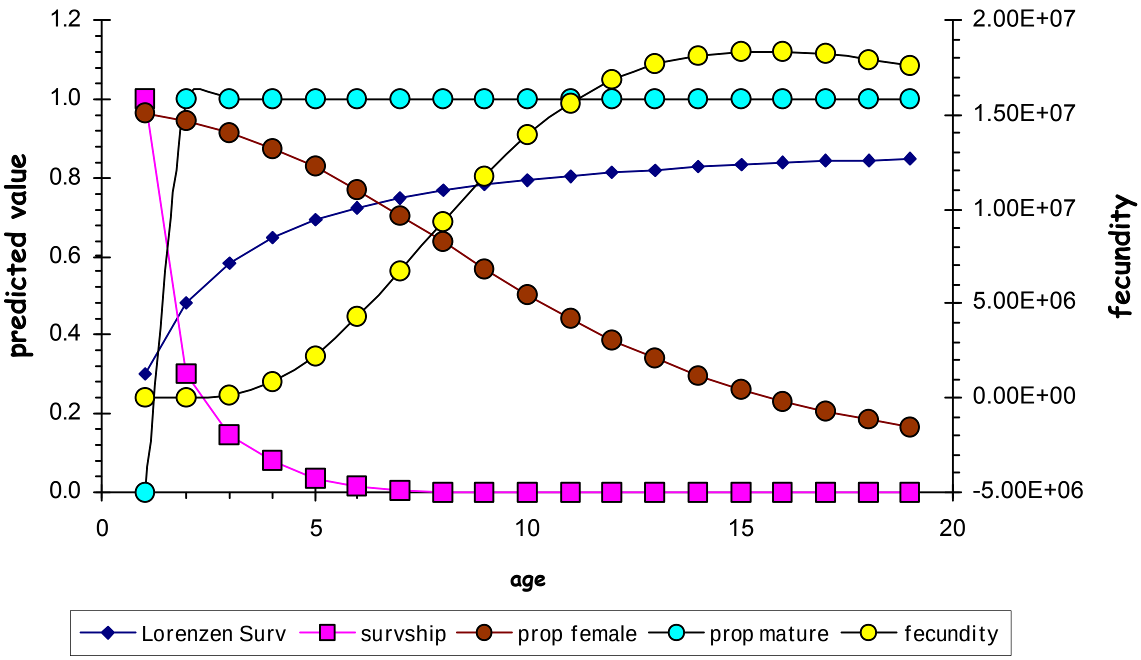

Figure 1.4- Graphical depiction of key population dynamic parameters over age for hogfish.

Figure 2.1.- Florida total marine recreational fishing trips and reef fish fishing trips for the period 1982 to 2001 estimated from the MRFSS database.

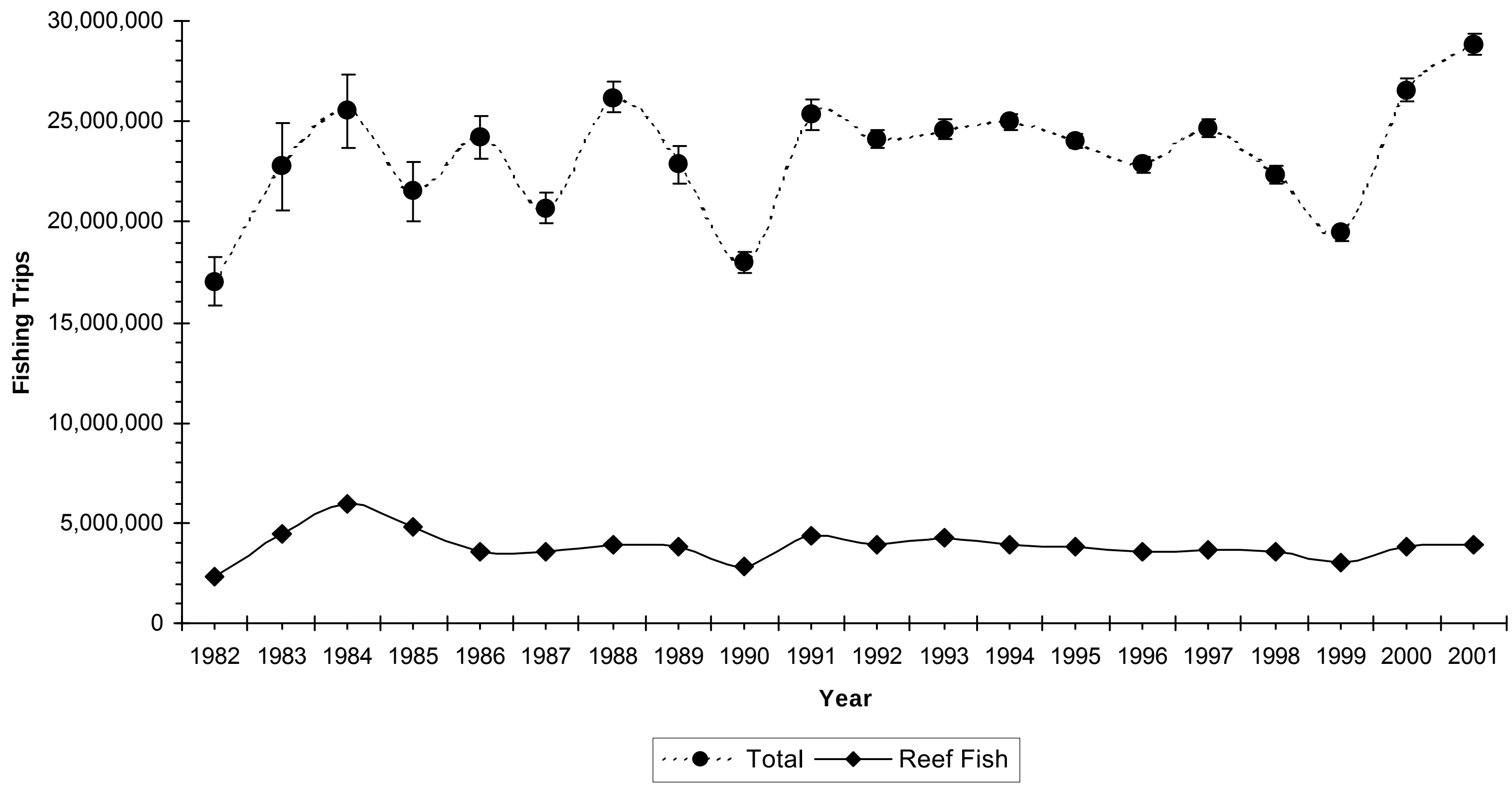

Figure 2.2.- Spatial extent of commercial and recreational fisheries for hogfish in Florida.

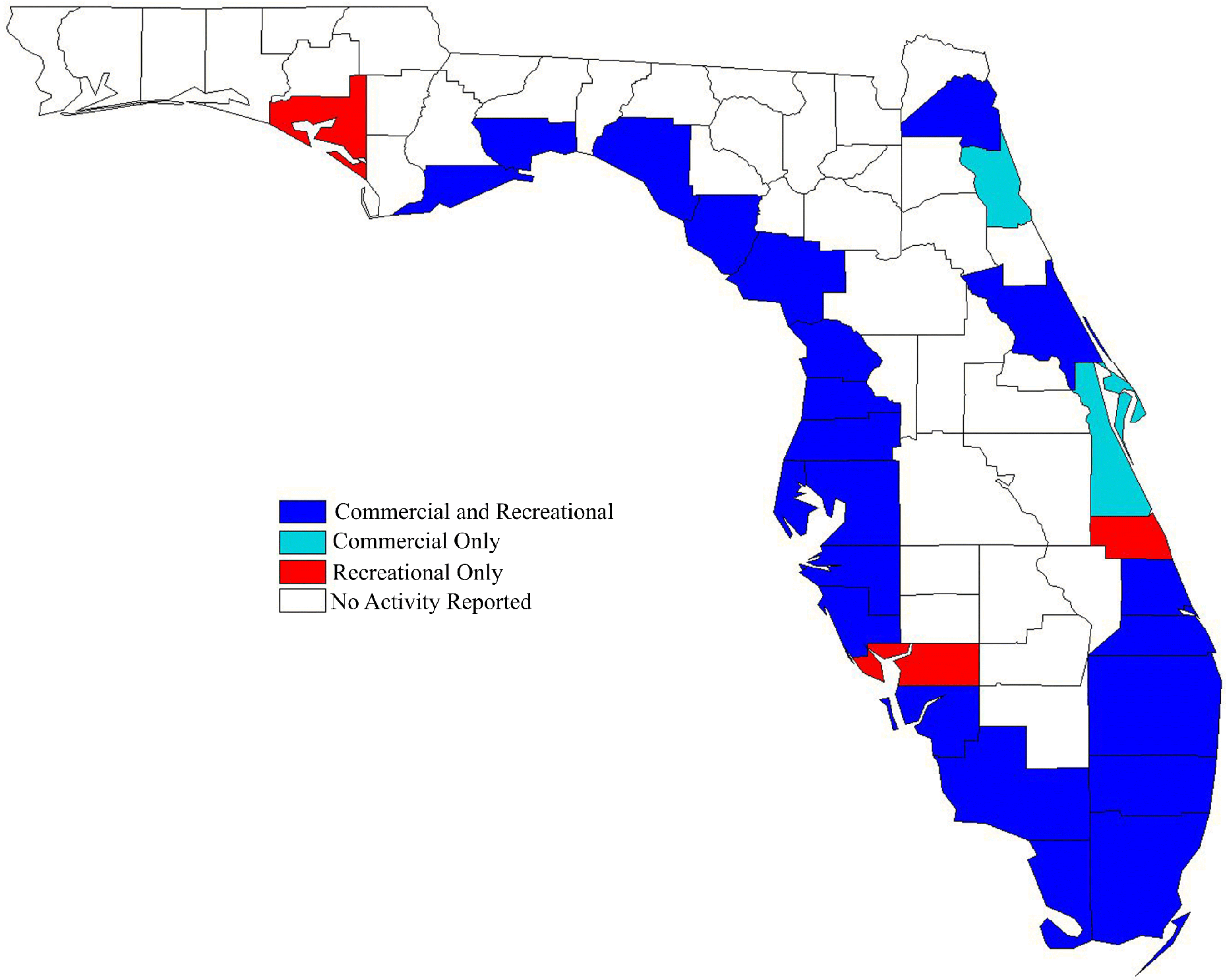

Table 2.1.- Total number of MRFSS intercept surveys conducted in Florida, 1982-2001, and the corresponding number of intercepts of fishing trips targeting the snapper-grouper complex within the hogfish geographical area.

	Florida Total		Reef Fish, Hook-Line		Reef Fish, Spear	
Year	**Intercepts**	**Trips**	**Intercepts**	**Trips**	**Intercepts**	**Trips**
1982	5271	6534	723	1070	36	53
1983	4350	5300	965	1256	30	38
1984	4869	5986	1155	1577	15	22
1985	4312	4886	1047	1242	2	2
1986	5730	6822	1221	1557	17	24
1987	4894	6113	1056	1461	68	107
1988	7772	9470	1430	1968	55	78
1989	6237	7624	1201	1721	29	47
1990	5491	6451	950	1259	33	52
1991	6569	8001	1207	1671	26	32
1992	13650	16518	2656	3468	80	117
1993	14145	16519	2491	3247	55	77
1994	16824	19296	2631	3412	71	104
1995	14865	16972	2299	2951	43	65
1996	13494	15502	2311	2974	68	99
1997	14374	17915	2500	3459	47	79
1998	18474	24070	3447	5280	71	100
1999	26150	36243	4566	7232	98	163
2000	22142	33370	3910	6849	37	57
2001	23496	34246	3690	6578	63	100

Table 2.2.- (a) Annual number of fishing trips targeting hogfish in Florida by fleet (commercial vs. recreational) and gear type. (b) Total annual hogfish trips and catch by fleet, 1982-2001.

(a) Year	Comm. Hook-Line	Comm. Trap	Comm. Spear	Comm. HL+Spear	Comm. H-L + Trap	Comm. Other	Comm. N/R	Rec. Hook-Line	Rec. Spear
1982								2,246,596	98,112
1983								4,371,009	104,274
1984								5,865,534	72,798
1985							109,786	4,808,019	7,256
1986							106,697	3,503,880	39,113
1987							131,284	3,331,454	188,972
1988							118,135	3,783,857	129,555
1989							140,520	3,709,383	83,585
1990							134,159	2,759,092	98,532
1991	11,329	10,037	1,854	124	504	15,812	81,510	4,271,709	61,985
1992	25,332	20,573	3,514	510	1,199	31,228	32,928	3,786,840	108,928
1993	34,727	24,974	3,947	542	1,509	31,663	6,769	4,161,496	90,655
1994	33,440	26,382	4,856	716	1,235	32,806	2,604	3,806,049	108,743
1995	31,595	26,216	5,324	549	1,111	16,309	1,854	3,710,154	75,618
1996	30,306	26,929	4,749	587	1,027	6,744	2,116	3,466,886	104,214
1997	30,206	27,627	5,291	720	794	6,535	1,909	3,533,807	72,340
1998	27,299	23,722	4,625	757	491	6,595	1,851	3,510,783	69,149
1999	25,456	23,419	4,494	652	514	5,537	1,900	2,984,428	64,809
2000	22,557	20,761	5,201	573	704	6,477	1,947	3,833,632	32,800
2001	22,333	17,714	4,739	528	584	6,475	441	3,847,929	54,759

(B)	Commercial		Recreational	
Year	**Trips**	**Catch (kg)**	**Trips**	**Catch (kg)**
1982			2,344,708	73,571
1983			4,475,284	109,576
1984			5,938,332	153,020
1985	109,786	19,930	4,815,275	48,059
1986	106,697	24,526	3,542,993	121,352
1987	131,284	33,121	3,520,426	238,883
1988	118,135	34,194	3,913,412	196,400
1989	140,520	49,512	3,792,968	105,524
1990	134,159	52,325	2,857,624	114,125
1991	121,170	48,465	4,333,694	114,808
1992	115,284	53,723	3,895,768	170,983
1993	104,131	61,537	4,252,151	202,741
1994	102,039	42,147	3,914,793	161,037
1995	82,958	29,261	3,785,771	153,684
1996	72,458	27,361	3,571,100	113,668
1997	73,082	29,705	3,606,147	112,931
1998	65,340	21,221	3,579,932	63,946
1999	61,972	20,899	3,049,236	72,211
2000	58,220	22,040	3,866,432	39,028
2001	52,814	20,255	3,902,688	68,472

Table 2.3.- Annual mean individual hogfish weight in the recreational fishery estimated from MRFSS intercept survey.

Year	n	Mean Weight (kg)	95% Confidence Interval Lower	Upper
1981	101	0.575	0.517	0.637
1982	19	0.728	0.443	1.079
1983	13	0.593	0.424	0.787
1984	23	0.562	0.466	0.666
1985	3	0.932	0.794	1.076
1986	65	0.660	0.556	0.772
1987	84	0.687	0.592	0.789
1988	45	0.950	0.807	1.104
1989	39	0.762	0.633	0.903
1990	30	0.748	0.610	0.899
1991	45	0.645	0.532	0.769
1992	97	0.717	0.627	0.813
1993	79	0.673	0.595	0.756
1994	115	0.666	0.614	0.720
1995	78	0.867	0.747	0.996
1996	71	0.832	0.750	0.919
1997	62	0.884	0.745	1.034
1998	75	0.767	0.692	0.846
1999	83	0.835	0.748	0.927
2000	36	1.057	0.935	1.186
2001	49	0.872	0.758	0.994

Table 2.4.- Results from the effort standardization and gear correction factor procedure.

Gear	Fleet	Effort Unit	n	Parameter Estimate	SE(Estimate)	Predicted CPUE	GCF
Spear	Comm.	trip-hour	284	0.6778	----	0.28553	1.0000
Hook-Line	Comm.	trip-hour	344	-2.0162	0.0781	0.01930	0.0676
Trap	Comm.	trip	155	0.8813	0.1133	0.34995	1.2256
H-L + Spear	Comm.	trip	240	1.1918	0.0937	0.47737	1.6719
H-L + Trap	Comm.	trip	147	0.3765	0.1143	0.21125	0.7399
Other	Comm.	trip	181	0.1849	0.1037	0.17442	0.6109
N/R	Comm.	trip	200	-0.4958	0.1005	0.08830	0.3092
Hook-Line	Rec.	person-hour	137	-1.3169	0.1192	0.03885	0.1361
Spear	Rec.	person-hour	144	0.5165	0.1183	0.24300	0.8511
Intercept				-1.9312	0.0382		

Table 2.5.- Standardized hogfish fishery catch and effort for the Commercial and Recreational fleets from 1982-2001.

	Commercial		Recreational		Combined		Combined
Year	**effort_s**	**catch_w**	**effort_s**	**catch_w**	**effort_s**	**catch_w**	**CPUE**
1982			570928	73571	570928	73571	0.1289
1983			598462	109576	598462	109576	0.1831
1984			534300	153020	534300	153020	0.2864
1985	339502	19930	314671	48059	654173	67989	0.1039
1986	329951	24526	310762	121352	640712	145878	0.2277
1987	405984	33121	713983	238883	1119967	272004	0.2429
1988	365319	34194	551537	196400	916856	230594	0.2515
1989	434544	49512	316803	105524	751347	155036	0.2063
1990	414873	52325	528603	114125	943477	166450	0.1764
1991	302716	48465	381864	114808	684580	163273	0.2385
1992	210318	53723	506178	170983	716496	224706	0.3136
1993	146077	61537	465903	202741	611980	264278	0.4318
1994	142415	42147	489969	161037	632383	203184	0.3213
1995	128601	29261	470010	153684	598610	182945	0.3056
1996	121212	27361	497284	113668	618496	141029	0.2280
1997	123473	29705	435395	112931	558868	142636	0.2552
1998	107650	21221	406797	63946	514447	85167	0.1656
1999	104754	20899	360723	72211	465478	93110	0.2000
2000	106642	22040	328975	39028	435617	61068	0.1402
2001	90000	20255	385440	68472	475440	88727	0.1866

Table 2.6.- (a) RVC survey strata description and sample size (number of primary sampling units, area) by spatial management zone (fishing and no-take MPAs). (b) Stratification scheme by survey period for hogfish mean density. (c) Survey sample sizes, hogfish density estimates and coefficient of variation (CV) by year (*n* is number of primary sampling units, *nm* is number of diver stations).

(a)

		Fishing Zones		No-Take MPAs	
Stratum ID	**Description**	**Primary Units (no.)**	**Area (km^2)**	**Primary Units (no.)**	**Area (km^2)**
S01	Inshore reef	149	5.96	29	1.16
S02	Mid-channel patch reef	3467	138.68	55	2.20
S03	Offshore patch reef	1162	46.48	93	3.72
S04	Back reef / rubble	440	17.60	74	2.96
S05	Forereef, depth <6 m	1228	49.12	218	8.72
S06	Forereef, depth 6-18 m	5275	211.00	261	10.44
S07	Forereef, depth >18 m	1504	60.16	75	3.00

(b)

Time Period	**Stratification Description, Hogfish Density Estimation**
all years	Back reef eliminated (S04)
1979-1987	Simple random design (1-strata)
1988-1996	3-strata: S01, S02, S03 combined; S05; S06 and S07 combined; fishing and MPA zones combined
1997-1999	10-strata: S06 and S07 combined; all others individual; fishing and MPA zones separate
2000-2001	11-strata: S06 and S07 combined in MPAs; all others individual; fishing and MPA zones separate

Table 2.6.- (cont.)

(c)

Year	No. of Strata	*n*	*nm*	Mean Density (no. per 177 m^2)	CV (%)
1979	1	4	13	0.0000	0.00
1980	1	9	145	0.2630	68.25
1981	1	25	213	0.0556	28.19
1982	1	19	189	0.0783	31.86
1983	1	16	505	0.2286	44.90
1984	1	15	227	0.1746	43.37
1985	1	8	124	0.0668	70.28
1986	1	8	32	0.0875	73.04
1987	1	6	70	0.0558	50.22
1988	3	22	263	0.1237	33.63
1989	3	24	318	0.2017	23.96
1990	3	23	282	0.1532	19.38
1991	3	20	280	0.1902	22.77
1992	3	21	256	0.3189	22.95
1993	3	22	196	0.1902	29.83
1994	3	23	91	0.2504	29.51
1995	3	55	283	0.2533	17.84
1996	3	38	157	0.1495	25.63
1997	10	68	404	0.3064	24.35
1998	10	78	462	0.2631	20.80
1999	10	159	438	0.5993	17.04
2000	11	215	487	0.7287	12.24
2001	11	294	720	1.2959	9.98

Figure 2.3.- Total annual hogfish (a) catch, (b) effort, and (c) CPUE for recreational hook-line and spear gears.

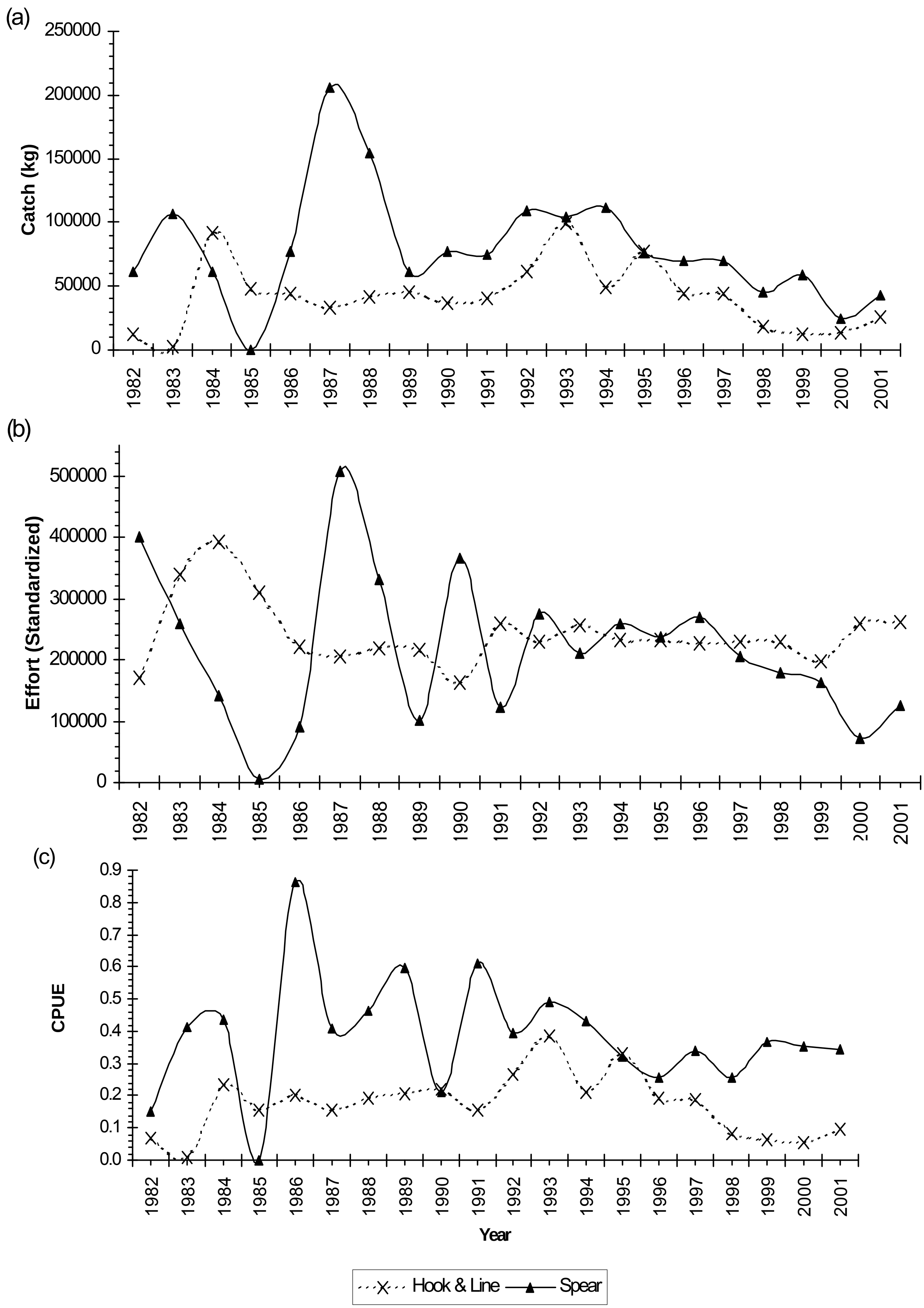

Figure 2.4.- Total annual hogfish (a) catch, (b) effort, and (c) CPUE for principal commercial gear categories.

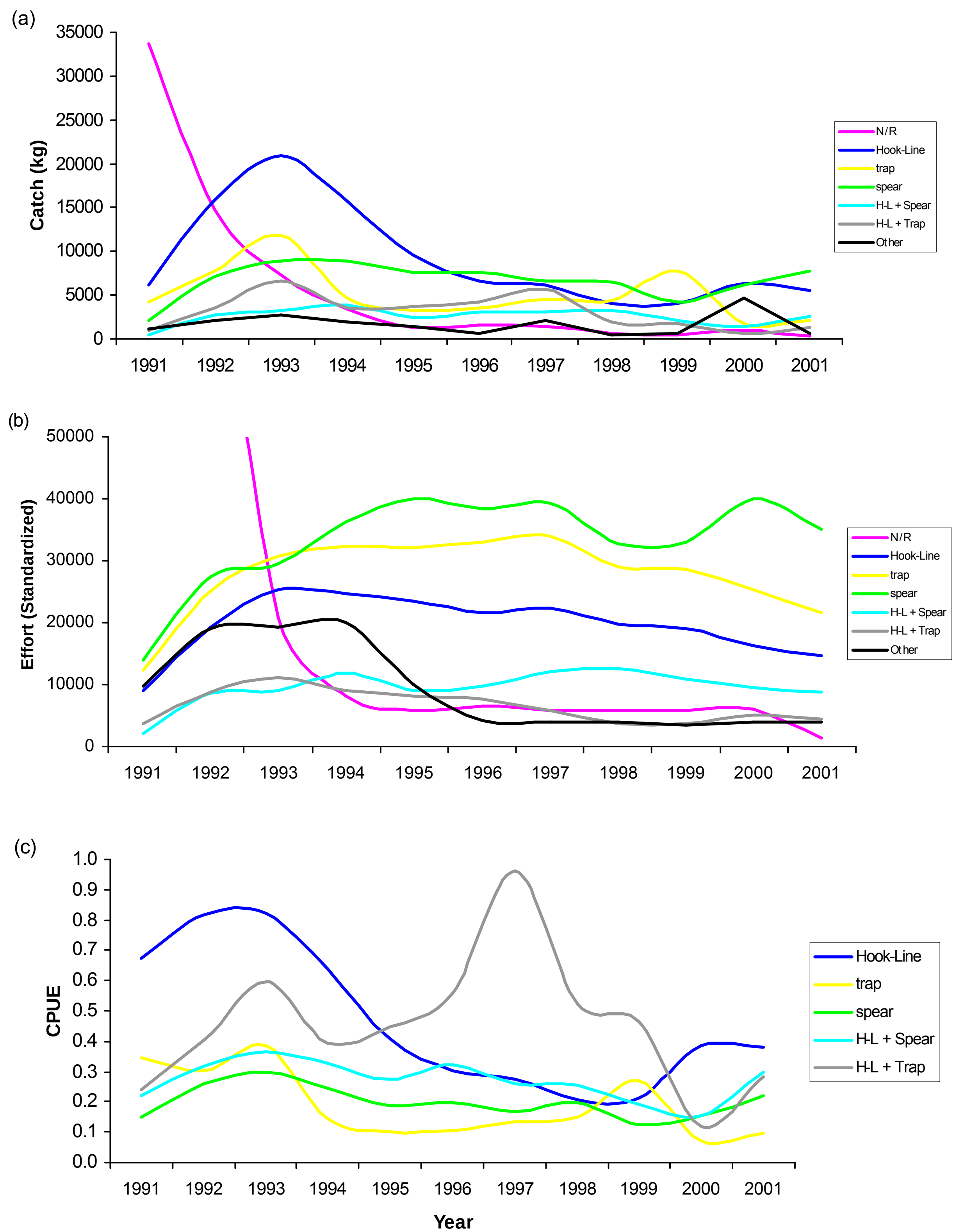

Figure 2.5.- Comparison of recreational and commercial total hogfish (a) catch, (b) effort, and (c) CPUE in Florida.

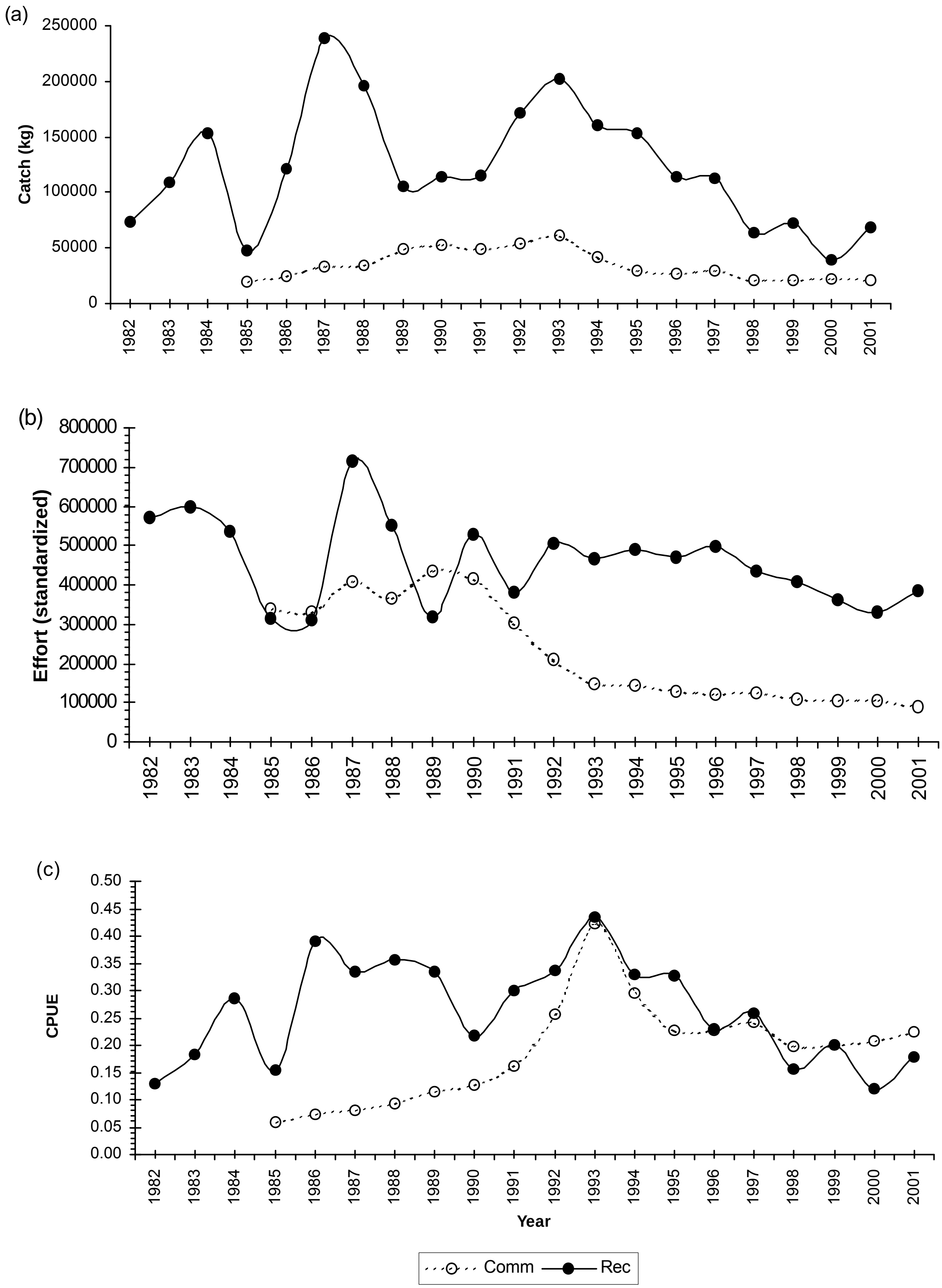

Figure 2.6.- Hogfish population abundance indices: (a) juvenile mean density, 1979-2001, estimated from the fishery-independent RVC survey; (b) exploited phase density, 1979-2001, estimated from RVC survey; (c) total combined commercial and recreational fishery CPUE, 1982-2001.

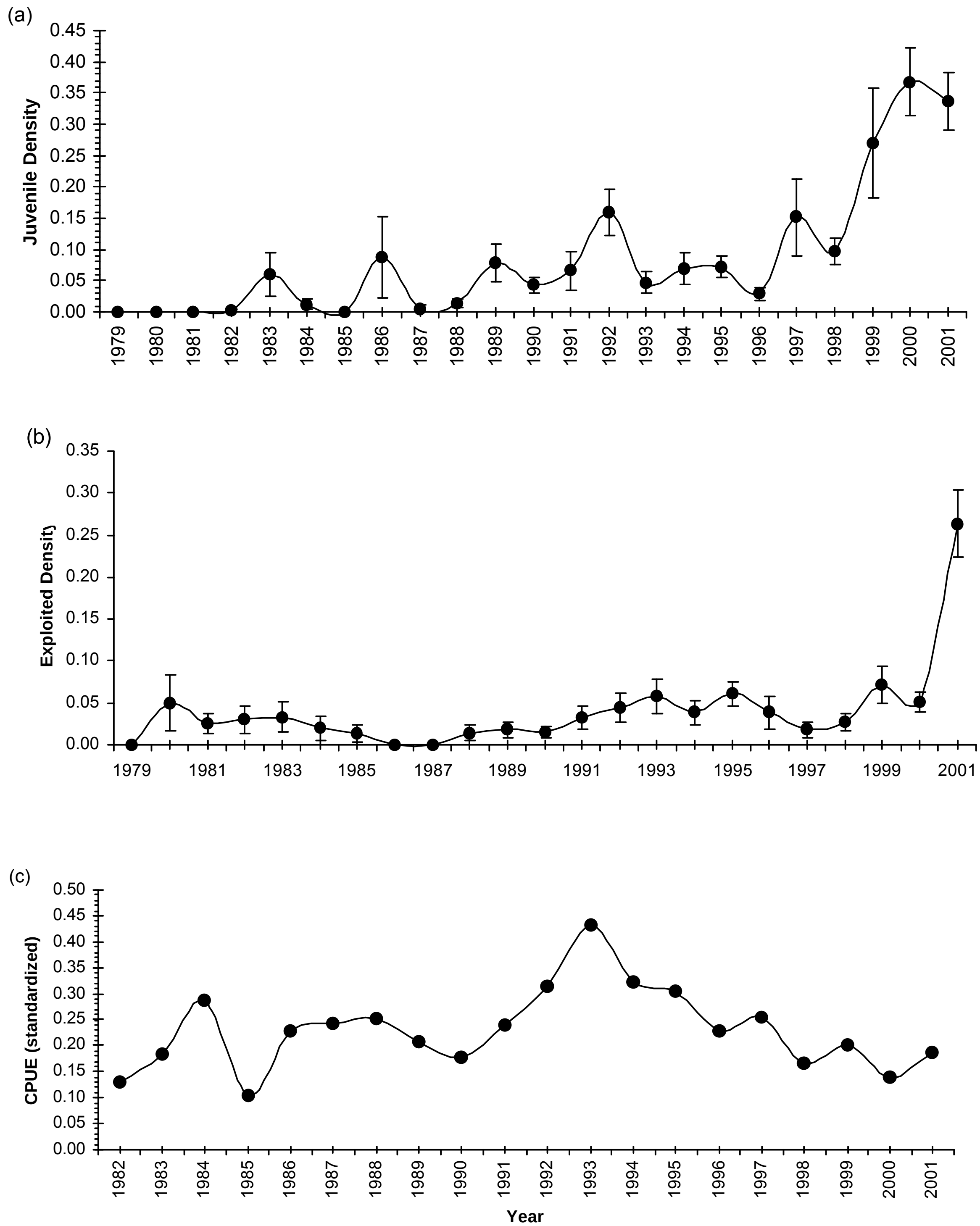

Figure 3.1 - Flow chart showing the 10 steps in the Florida hogfish fishery stock assessment.

Assimilation of Fishery-Independent and Fishery-Dependent Data

Step 1: Conduct data assimilation and standardization of RVC fishery-independent data for hogfish in year *t*. Intercalibrate data by life stage, site, and year. Compute population abundance by 1 cm size categories.

Step 2: Conduct data assimilation and standardization for fishery-dependent data (i.e., MRFSS, headboats, BNP and commercial trip ticket data). Intercalibrate CPUE data and standardize effort data for the fleet types.

⇓

Stock Assessment Analyses

Step 3: Use intercalibrated fishery-dependent size and abundance data integrated over the range of exploitable sizes data to compute annual estimates of $\bar{L}$ and associated 95% confidence intervals.

⇓

Step 4: Use $\bar{L}(t)$ estimates and population dynamics parameters (**Table 1.2**) to parameterize LBAR model (Ault et al. 1996, FAO 1997) to estimate annual total and fishing mortality rates as $\hat{F}(t) = \hat{Z}(t) - M$ for each species by year for the several data sources (i.e., time series of RVC, headboat, trip ticket, and MRFSS data).

⇓

Step 5: Parameterize stock synthesis model with fishery-dependent commercial and recreational fishery catch and effort data (**Table 2.5**).

⇓

Step 6: Use ASPIC and PRODFIT surplus production models to compute fishing mortality rates, recruitment, and population sizes.

⇓

Step 7: Use Stock Synthesis models and ADAPT-type VPA methods to estimate *F* for age-structured hogfish population and to compute recruitment anomalies and population sizes (in particular, estimate q, N_0, F, Y, Yopt and fopt.

⇓

Management Benchmark Analyses

Step 8: Use REEFS population simulation model (**Figure 4.2** and **Table 1.2**): (1) to compute expected $\bar{L}(t)$ given the population dynamics rates for hogfish and the estimated $\hat{F}$ parameter values estimated in the stock assessment analyses; (2) to compute YPR and assess growth overfishing; and, (3) to compute SSB for the fishery in unexploited and exploited states (i.e., F=0, $F=F_{msy}$,$F=F_{0.1}$, *and* $F=\hat{F}(t)$, respectively) and assess SPR for recruitment overfishing.

Step 9: Use REEFS to compute the limit control rule parameters $\hat{B}_0$, B_{msy}, $\hat{B}(t)$ to assess the effects of exploitation on hogfish.

⇓

Step 10: Conduct model assimilation and fishery risk assessment to make specific management recommendations on control strategies of F and L_c consistent with eumetric fishing principles and the precautionary approach of the MSFMCA that minimize the potential for overfishing identify the prospects for sustainability of the resource.

Figure 3.1.- Hogfish annual average abundance (number of fish) at size (cm) from 1979-2002 estimated by the RVC survey.

	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	995	11524	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10055	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1613	0	2357
6	0	0	0	0	0	0	0	0	0	0	0	7080	0	7689	0	0	0	0	10610	0	0	0	5063	0
7	0	0	0	0	0	0	0	0	0	0	4962	0	0	7908	0	0	3919	0	0	4994	0	1613	0	4727
8	0	0	0	0	0	0	0	0	0	0	0	0	0	27565	0	0	3919	10055	0	23771	0	8720	13770	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	19656	0	0	0	0	32826	0	4020	0	0	2357
10	0	0	0	0	5543	0	0	0	0	5942	16476	0	0	43158	0	15554	15138	10055	0	10524	0	45002	37940	9923
11	0	0	0	0	0	0	0	0	0	0	0	7080	0	0	0	0	9800	0	0	0	25257	7241	8011	120
12	0	0	0	0	11080	0	0	0	0	0	21438	0	0	42944	21020	5019	23050	10055	94185	18521	24099	97075	80071	52638
13	0	0	0	0	5543	0	0	0	0	0	9924	0	0	58537	10510	46659	15681	10055	40755	5841	12050	44657	32150	31172
14	0	0	0	0	11080	25397	0	0	0	31284	76449	7080	26864	86317	0	0	37377	10055	32019	40699	60491	95744	52578	50046
15	0	0	0	14948	22167	25397	0	0	24358	0	66705	23932	65366	82465	0	31105	63425	25390	103857	79022	352023	344221	226765	254712
16	0	0	0	0	6926	25397	0	0	0	14163	26400	47867	35818	46996	33443	46659	3919	2641	56284	31517	102580	137401	87747	83512
17	0	0	0	0	58178	0	0	0	0	0	4962	0	8955	35469	10510	15554	5606	0	15172	41124	157894	128168	141005	95972
18	0	0	0	0	11080	0	0	0	0	7081	32952	57637	24924	31411	68796	30612	13441	20108	27909	29441	60410	218464	194590	134070
19	0	0	0	0	29093	0	0	267279	0	0	0	0	17909	0	0	15554	9800	0	44782	4727	85948	9253	127546	37293
20	0	100406	19967	0	69265	50794	20413	0	0	48408	54386	31015	39326	72425	33443	58626	55380	31950	101364	104813	150283	256576	478429	296299
21	0	0	0	0	23549	0	0	0	0	5942	0	0	0	15813	0	0	10165	10055	3094	56336	57170	38224	87223	15186
22	0	0	0	0	67876	25397	0	0	48713	31284	78215	7080	21417	55121	10510	86141	16046	28094	30735	50562	66266	61558	159396	153189
23	0	0	0	14948	49870	25397	0	0	0	0	37914	16852	8955	7908	0	0	14359	50274	5696	38713	55396	15249	143393	92227
24	0	0	0	0	66493	25397	0	0	24358	21244	0	0	21417	74561	0	74177	10165	32693	38097	27398	73931	45252	59725	73354
25	0	200813	39932	29896	44327	50794	40826	0	24358	58448	21438	85962	48281	11859	0	46415	53945	30735	96576	55105	92069	236051	440094	306687
26	0	100406	0	0	5543	0	0	0	0	38366	0	0	12462	27565	40161	56698	33003	0	32932	8040	101958	28455	70489	12762
27	**0**	**0**	**0**	**0**	**16623**	**0**	**20413**	**0**	**0**	**7081**	**0**	**7080**	**0**	**7908**	**0**	**15554**	**16957**	**22069**	**52283**	**33279**	**16886**	**78132**	**182848**	**56055**
28	0	0	0	44844	16623	50794	40826	0	24358	17121	61743	45177	26864	23722	22933	0	29412	10055	19555	9131	4785	12682	91436	35183
29	0	0	0	0	5543	0	20413	0	24358	24203	0	0	0	7908	40161	0	5646	0	10843	4328	15544	4384	64282	20840
30	0	200813	29949	59793	27703	126984	20413	0	0	30145	59348	69110	73204	55021	119468	101695	128563	38086	32691	32430	116036	157596	353192	408479
31	0	0	0	0	5543	0	0	0	0	23063	16476	0	0	7908	22933	0	8478	0	659	28618	23574	12988	24734	6195
32	0	0	9983	14948	27703	25397	20413	0	0	14163	21438	14163	3508	41456	10510	31105	8478	10055	4494	601	18084	9839	110146	24095
33	0	0	9983	0	11080	0	0	0	0	0	0	0	43949	0	10510	5019	24803	0	10610	104	15388	2590	89297	36436
34	0	0	0	0	0	0	20413	0	0	0	0	0	12462	7908	0	0	5881	36077	14900	2691	9533	0	18143	16148
35	0	0	59898	0	33247	76190	0	0	0	0	4962	33704	35818	0	71692	36124	32638	18039	12199	39797	23435	77455	238174	144081
36	0	0	0	0	11080	0	0	0	0	0	0	7080	12462	0	0	0	11755	20108	0	0	13792	4305	34629	25346
37	0	0	0	29896	11080	0	0	0	0	0	0	0	0	0	0	15554	0	10055	0	0	8681	5997	16967	34449
38	0	100406	0	14948	16623	0	0	0	0	0	0	0	0	0	10510	0	11766	0	0	3647	2880	2155	70612	34097
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4608	0
40	0	0	0	14948	16623	0	0	0	0	0	0	0	19477	35469	10510	15554	49311	0	3648	6496	24836	13360	100214	209919
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1578	0	14075
42	0	0	0	0	0	0	0	0	0	0	0	0	8955	0	0	0	0	0	0	0	0	8157	12825	6092
43	0	0	0	0	5543	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4727
44	0	0	0	0	0	0	0	0	0	0	0	0	0	7689	0	0	0	0	0	0	0	0	4788	0
45	0	0	0	0	0	0	0	0	0	0	0	0	3508	0	22933	0	0	0	7295	10175	29418	1548	62796	58555
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11766	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4529	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4011	9953
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	481	1168
50	0	0	0	0	5543	0	0	0	0	0	0	0	8955	23722	10510	15554	16314	0	0	188	2880	12640	14838	19150
51	0	100406	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9800	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4011	0
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11524	0	481	12221
56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	481	0
58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3919	0	0	0	0	0	0	0
61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
63	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
66	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
69	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4011	0
Total	0	803251	169711	239170	698173	533333	204131	267279	170501	377937	616184	467901	580855	974078	581066	764935	773630	456819	936066	803625	1830644	2225944	3958519	2885869

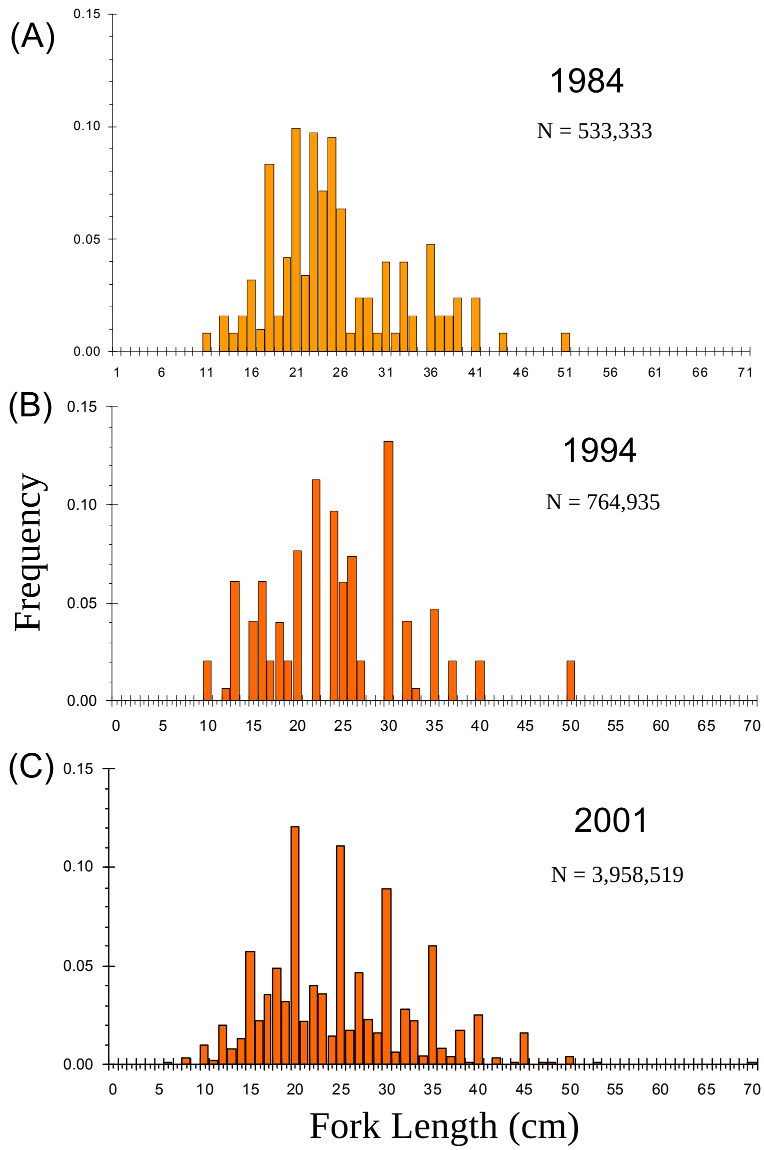

Figure 3.2.- Hogfish size (FL cm) frequency distribution for the years: (a) 1983, (b) 1994 and, (c) 2001.

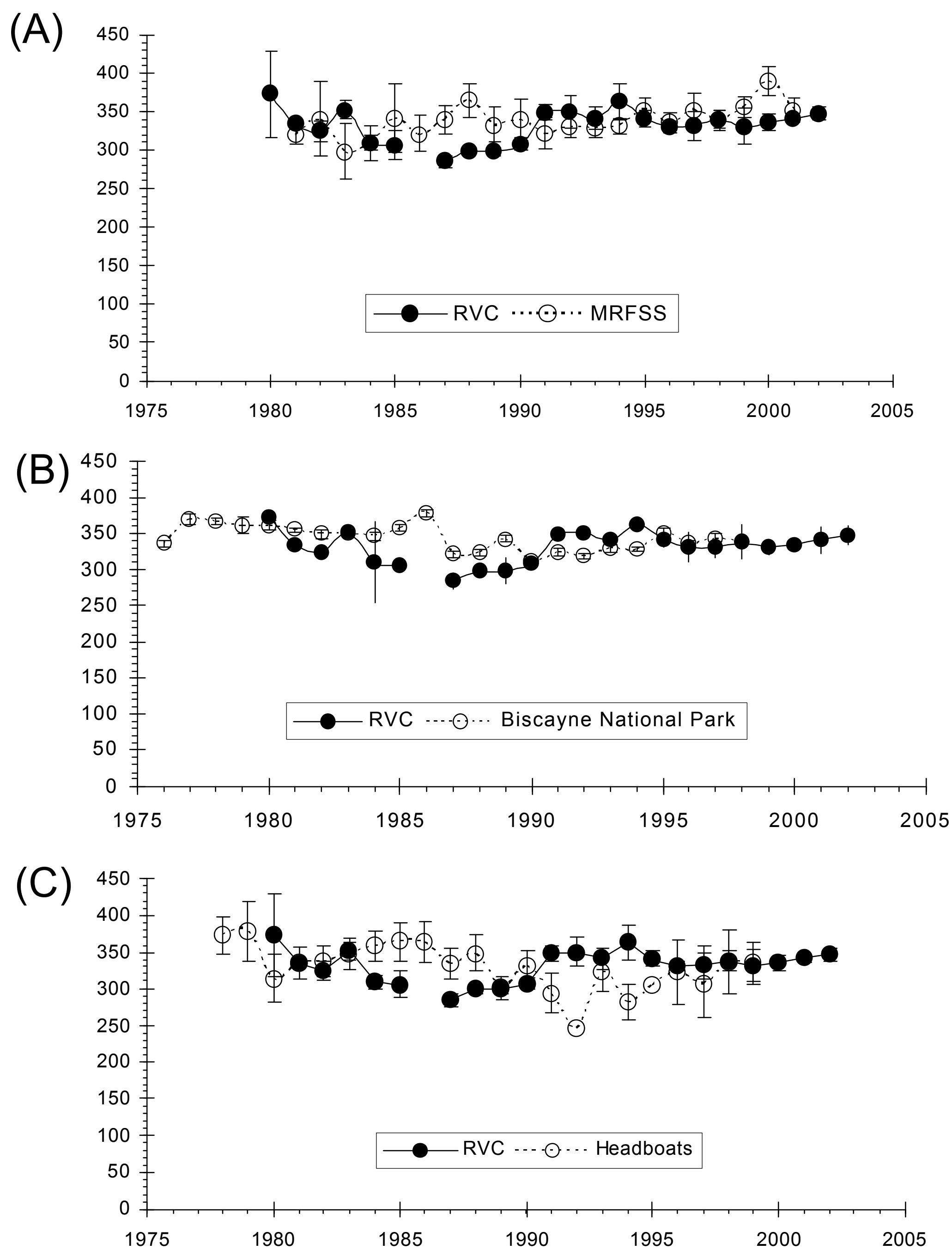

Figure 3.3.- Comparison of hogfish average size (FL mm) in the exploited phase estimated from: (a) reef fish visual census (RVC) and marine recreational fishery statistical survey (MRFSS); (b) RVC and ramp-intercept surveys at Biscayne National Park (BNP); and, (c) RVC and headboat survey.

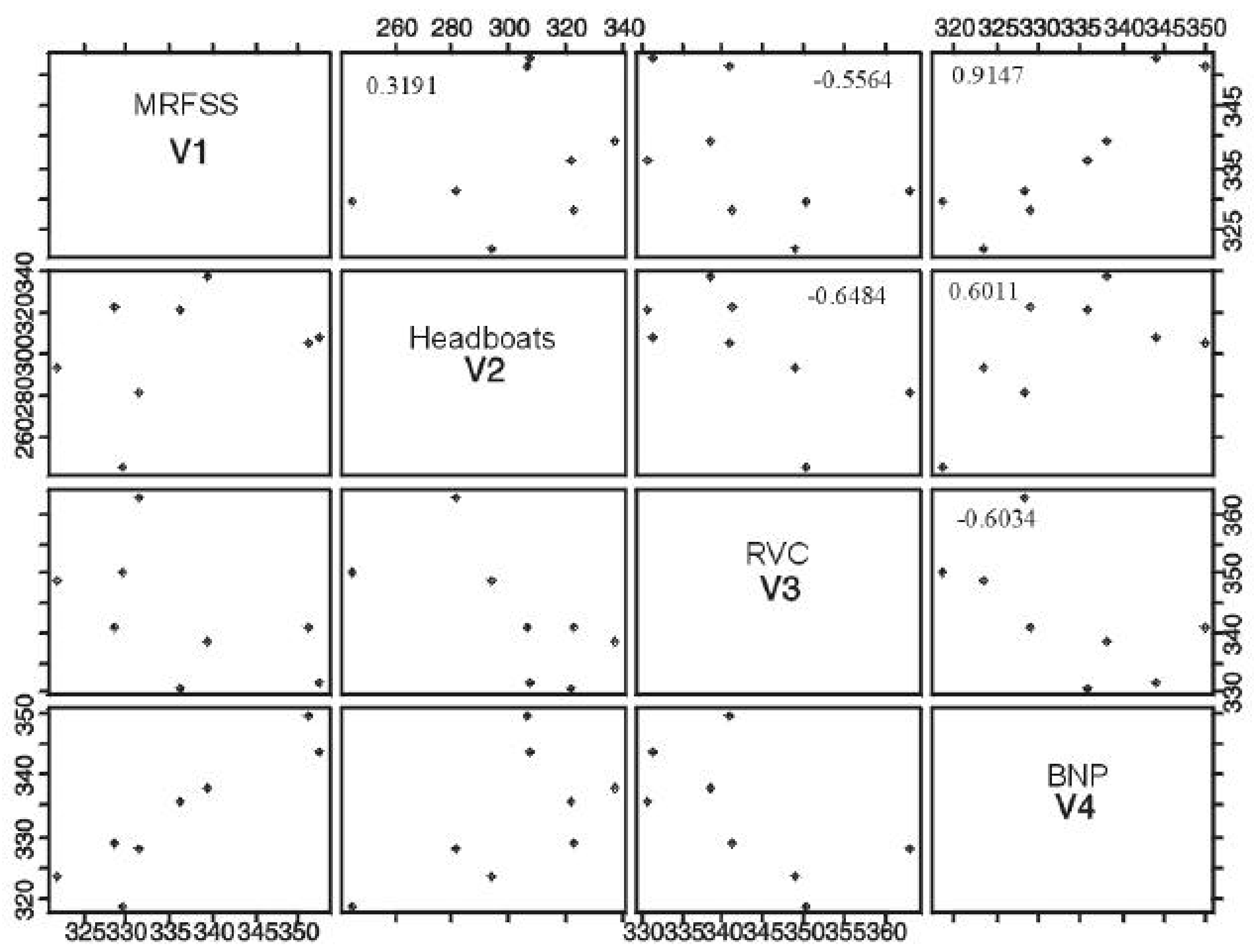

Figure 3.4.- Graphical correlation matrix of average size estimates provided by four independent fishery data sources: MRFSS, headboats, reef fish visual census (RVC), and Biscayne National Park (BNP) creel census, respectively.

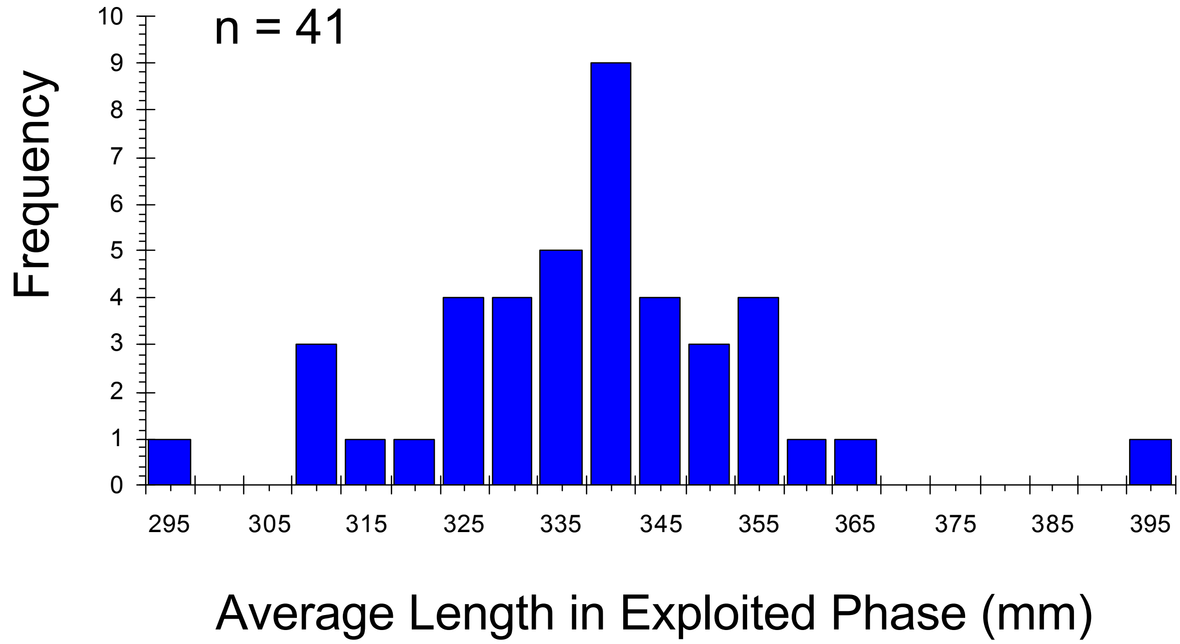

Figure 3.5.- Probability distribution of 41 “average size” estimates for the period 1990-2002 from all available fishery-independent and fishery-dependent data sources (i.e., RVC, MRFSS, BNP and Dry Tortugas 2000).

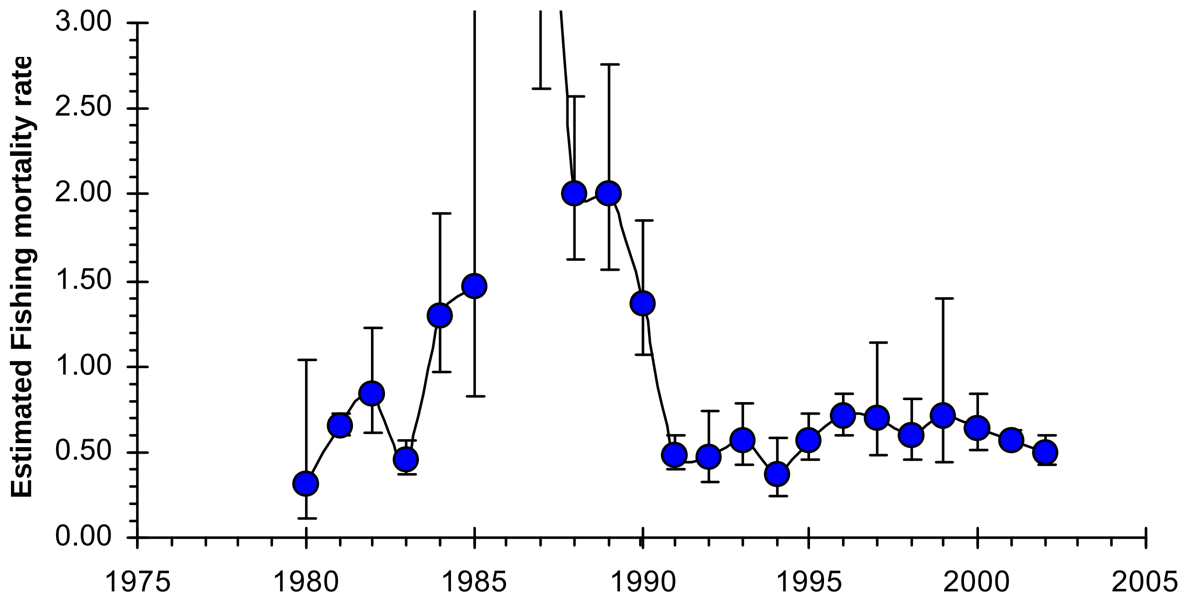

Figure 3.6.- Time series of fishing mortality rates estimated from the RVC database. Error distributions are 67%.

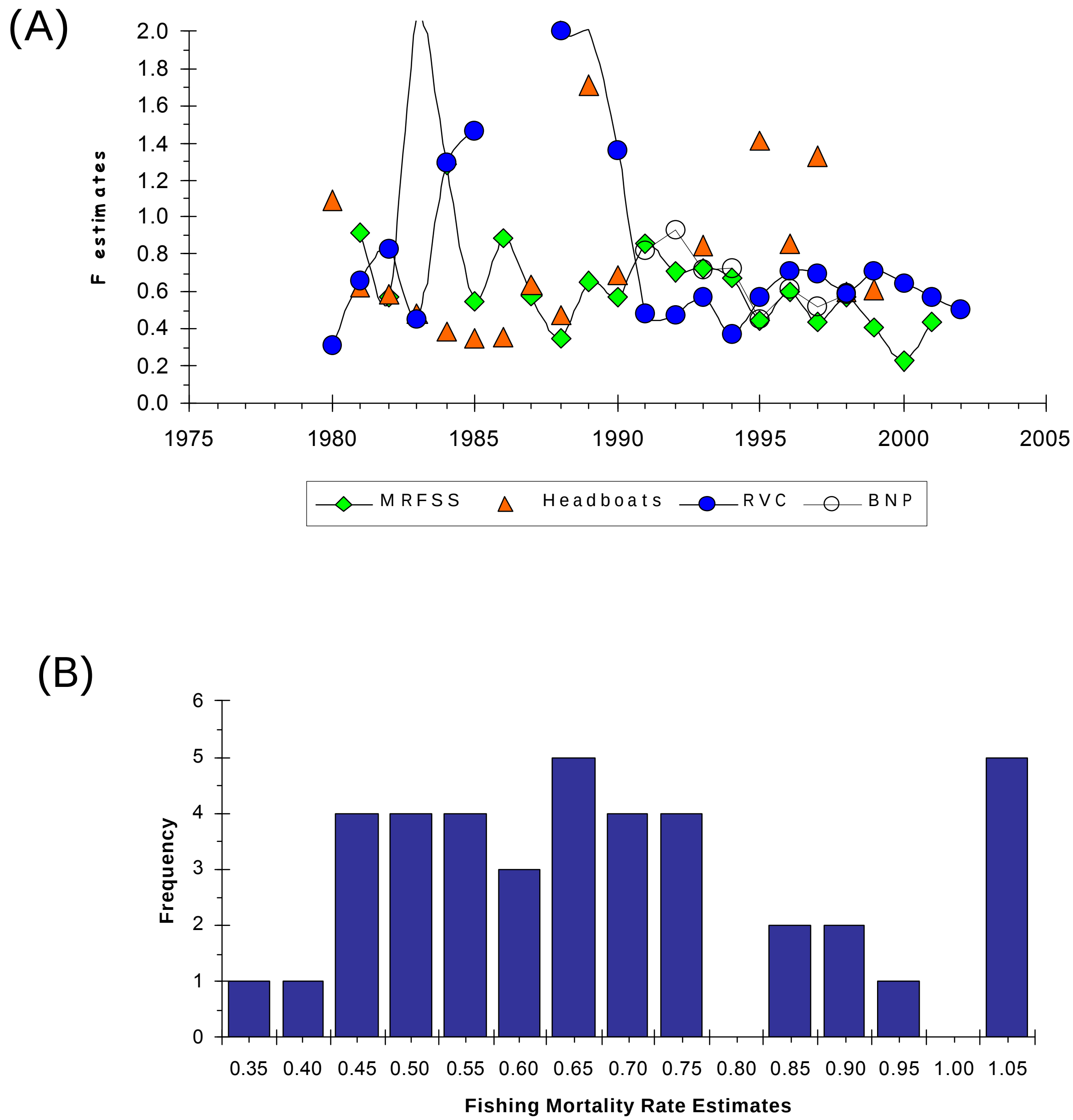

Figure 3.7.- (A) Comparison of age-based model estimated fishing mortality rates from data on average size statistics of the MRFSS, headboats, RVC surveys compared with the combined fishery-dependent and fishery-independent data fitting with the full stock synthesis analyses. (B) Estimates of fishing rate for the period 1991-2002 obtained from several sources of estimates for average sizes in the exploitable phase of the hogfish stock.

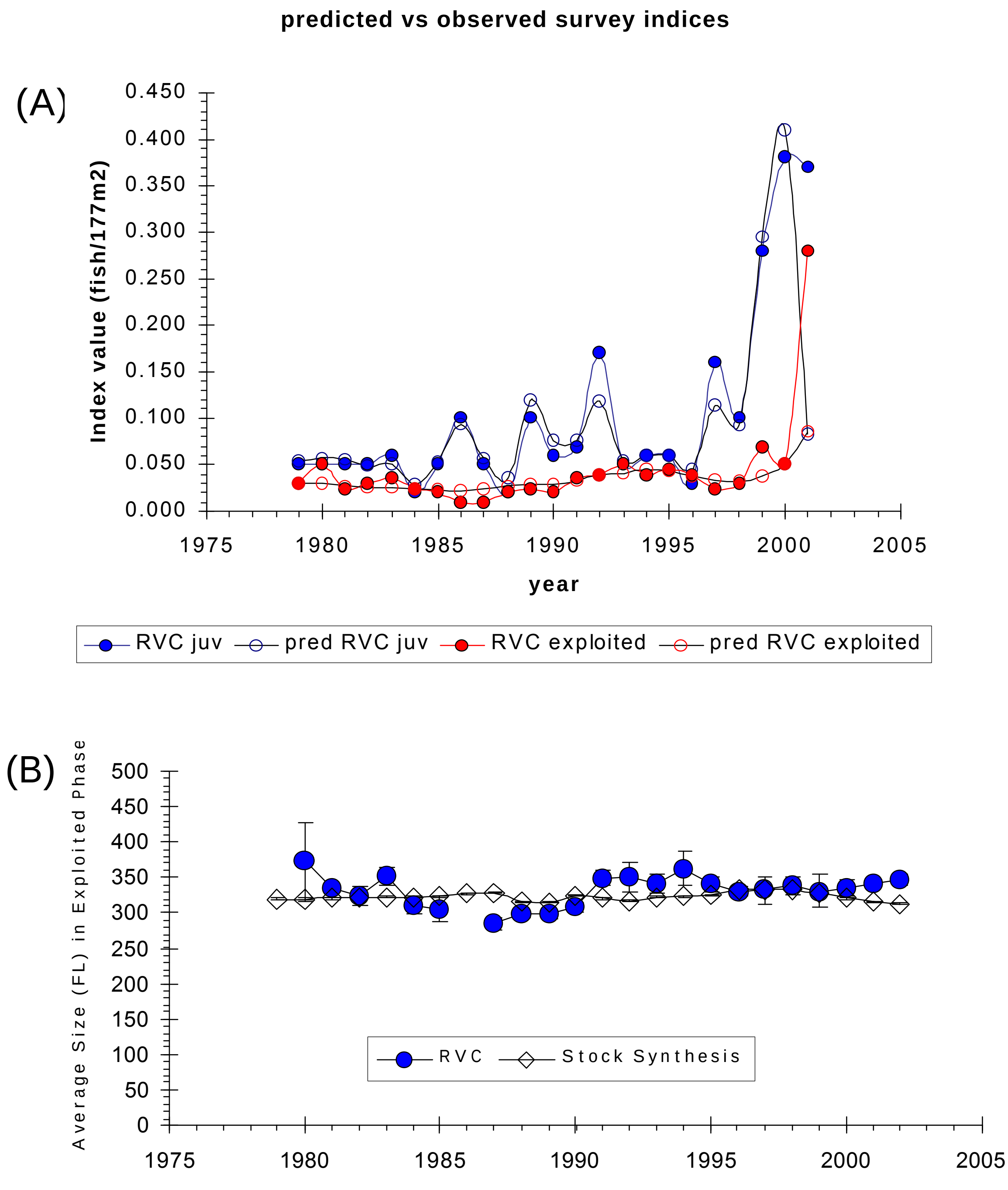

Figure 3.8.- Examples of the use of some "tuning" indices for the age-structured stock synthesis modeling of Florida hogfish: (A) RVC-based estimates of juvenile and exploited phase adults; and, (B) "average size" in the exploited phase, compared to model estimates.

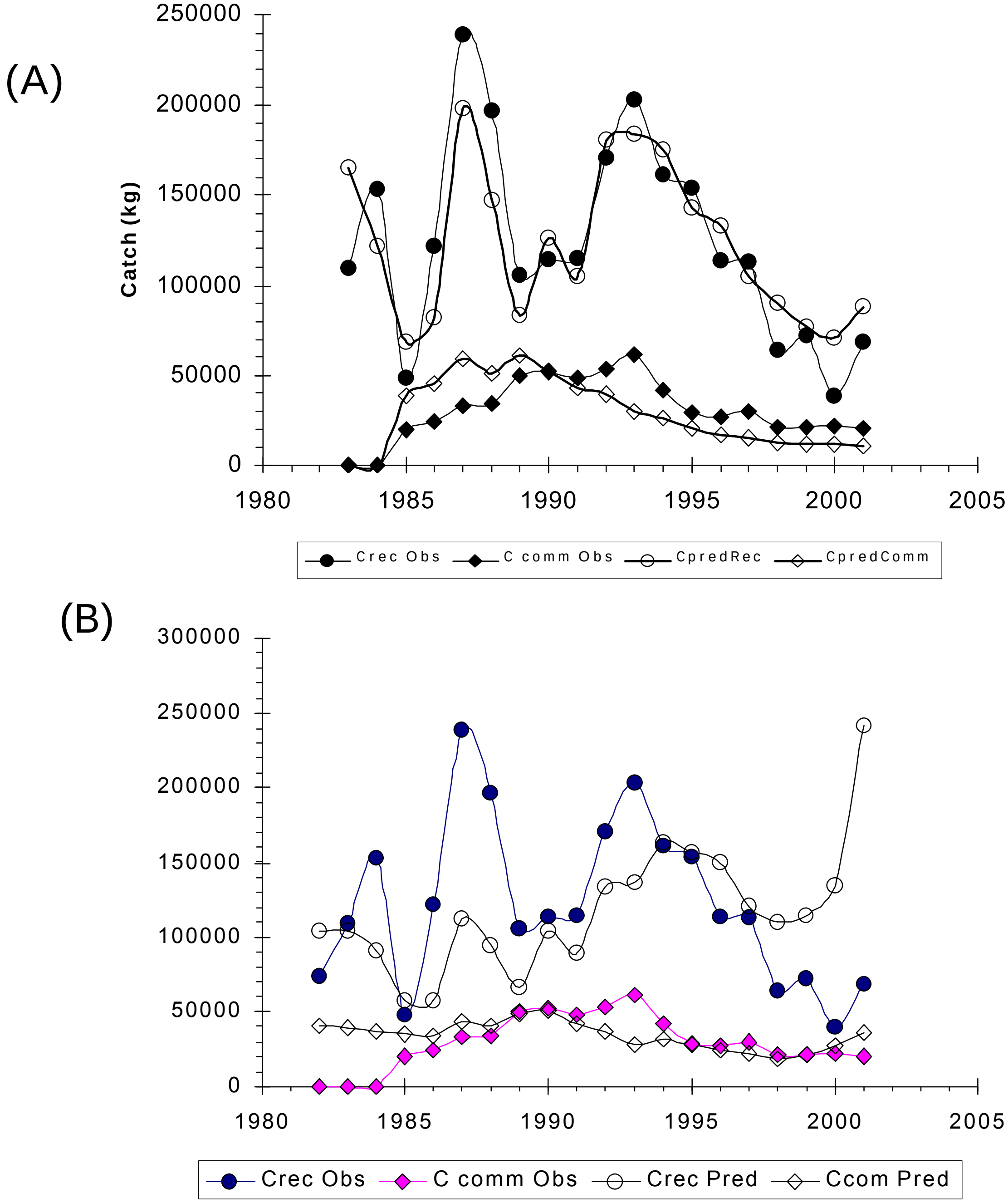

Figure 3.9.- Stock synthesis model estimates of Florida hogfish recreational and commercial catches in comparison to the observed catch time series: (A) continuous stock synthesis model fit to fishery-dependent data; and, (B) age-structured multi-objective stock synthesis model fit to fishery-dependent and fishery-independent data.

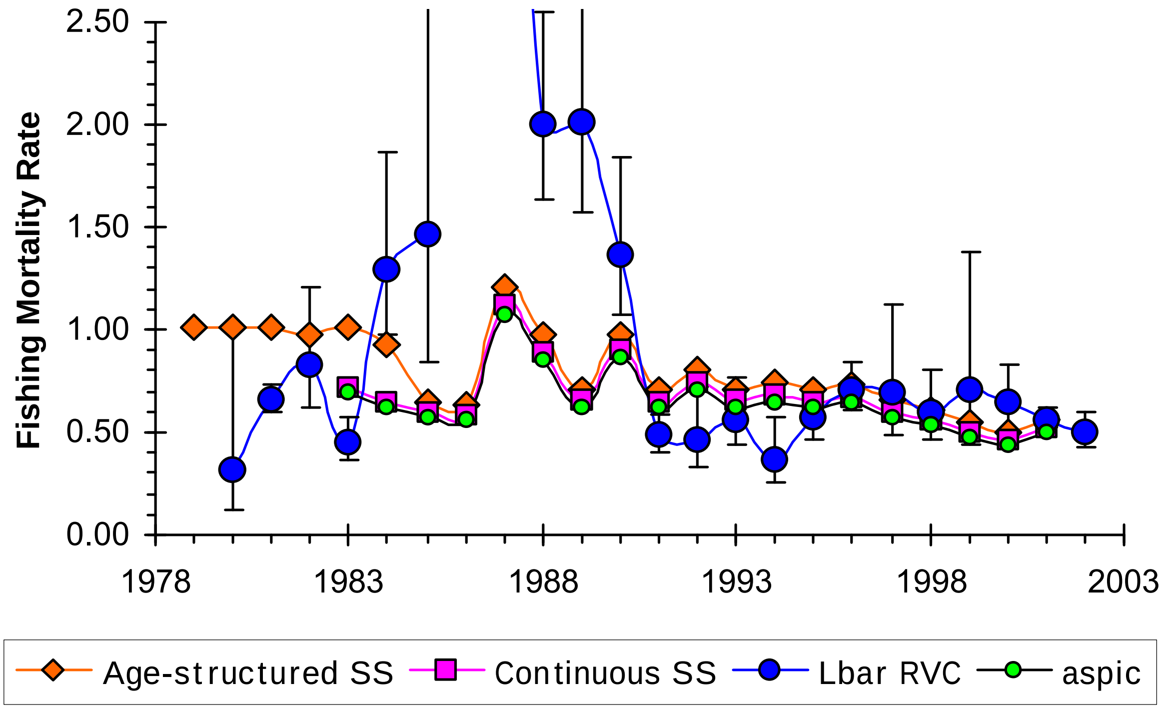

Figure 3.10.- Comparison of modeled fishing mortality rates estimated from continuous and age-structured stock synthesis, age-based average length estimator for RVC data, and ASPIC surplus production models.

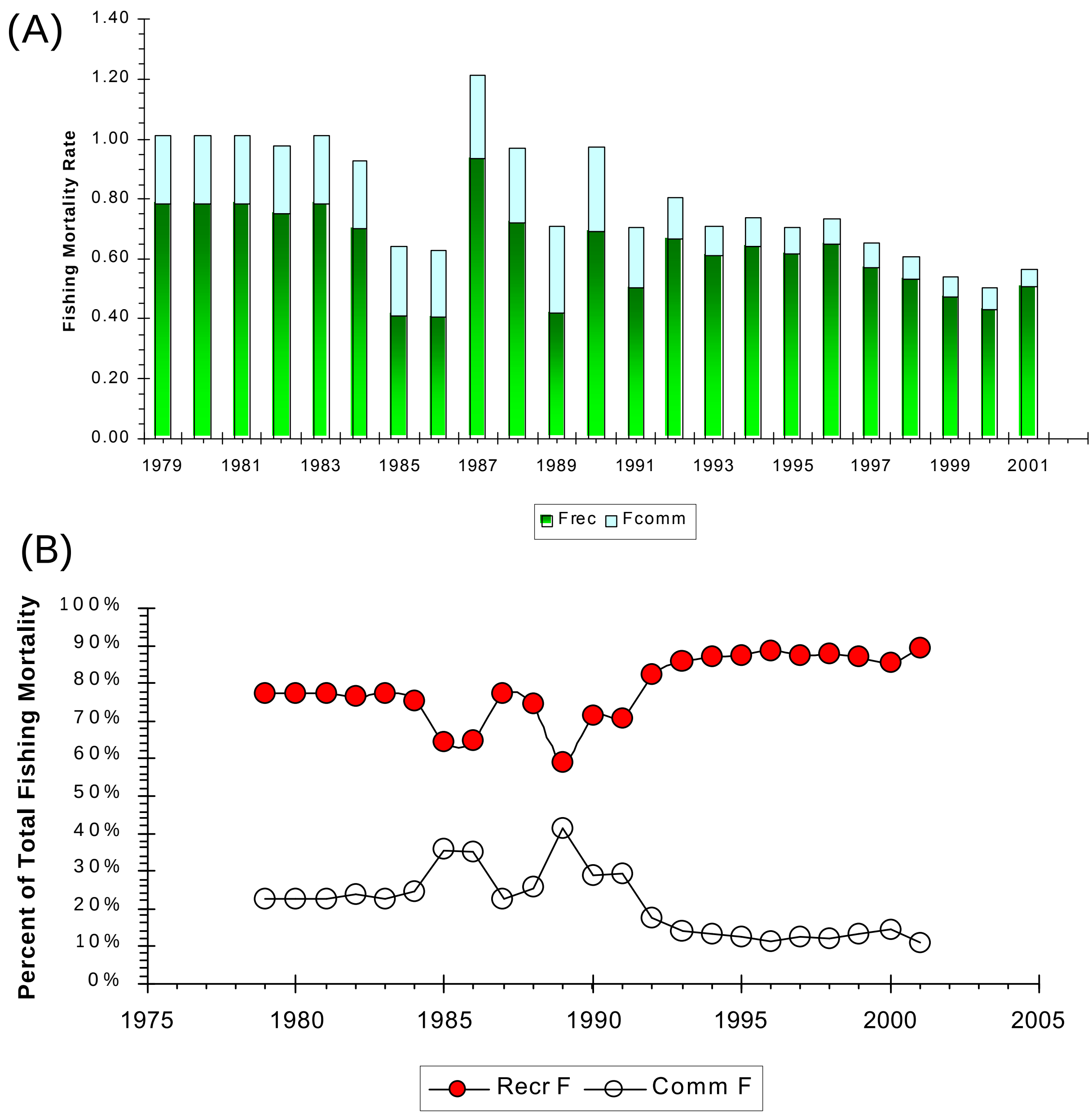

Figure 3.11.- Estimates of annual fishing mortality rates from 1982 to 2000 for Florida hogfish from stock synthesis modeling estimates of Florida hogfish: (A) estimated total fishing mortality rates by year showing commercial (light) and recreational (dark) fleet proportions; (B) percent of total F by recreational (solid circles) and commercial (open circles) fleets by year.

Year	Size Limits			Bag Limits			
	Sublegal	Legal	%Sublegal	Bag	Overbag	% Overbag	
1981	16	84	16.00				
1982	6	15	28.57	21	1	4.55	
1983	5	8	38.46	10	3	23.08	
1984	6	17	26.09	22	2	8.33	
1985	0	3	0.00	8	0	0.00	
1986	21	43	32.81	14	3	17.65	
1987	12	71	14.46	43	4	8.51	
1988	4	46	8.00	31	3	8.82	
1989	9	36	20.00	26	2	7.14	
1990	7	24	22.58	22	2	8.33	
1991	15	36	29.41	18	3	14.29	
1992	**17**	79	17.71	61	7	10.29	
1993	10	74	11.90	58	6	9.38	**Size & Bag Limit**
1994	8	105	7.08	69	4	5.48	**Implementation**
1995	6	76	7.32	47	4	7.84	
1996	5	62	7.46	43	1	2.27	
1997	4	58	6.45	42	1	2.33	
1998	5	75	6.25	63	0	0.00	
1999	2	86	2.27	65	3	4.41	
2000	1	43	2.27	28	0	0.00	
2001	3	51	5.56	53	1	1.85	

Table 4.1.- Compliance by recreational anglers with fishery management regulations such as minimum sizes and bag limits as set by the Florida Marine Fisheries Commission as determined from the MRFSS database. Shaded area indicates year of regulation implementation.

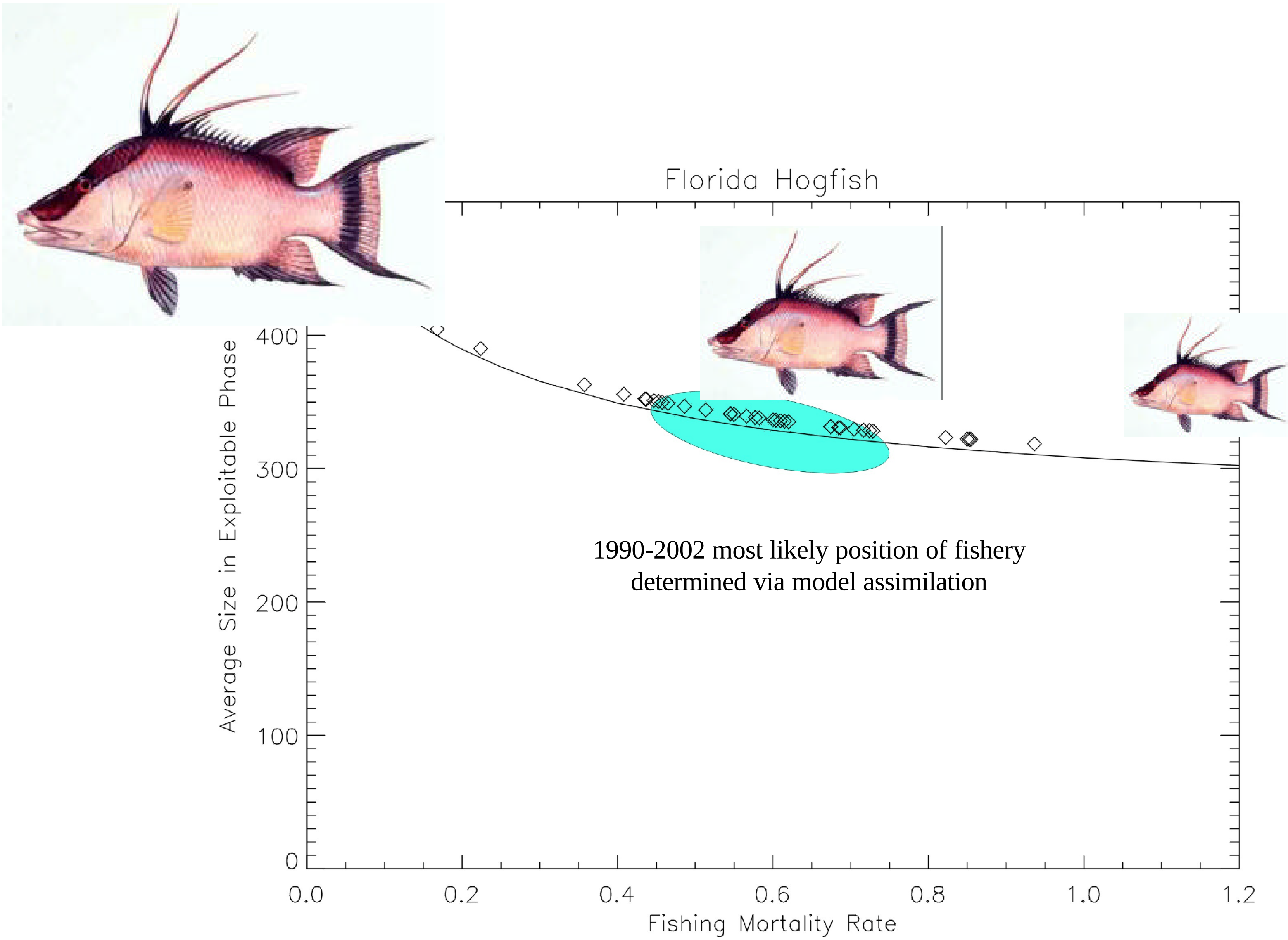

Figure 4.1.- Graphical example for Florida hogfish showing theory of reduction of average size (mm FL) in the exploited phase of the stock dependent on increasing fishing mortality. The shaded ellipse shows most likely status of the fishery during the period 1991-2002. Large darkened circle is the average size at F_{msy}. Diamonds above line are the 41 estimates of 'average size' derived from RVC, headboats, MRFSS and BNP data for the period 1991-2002.

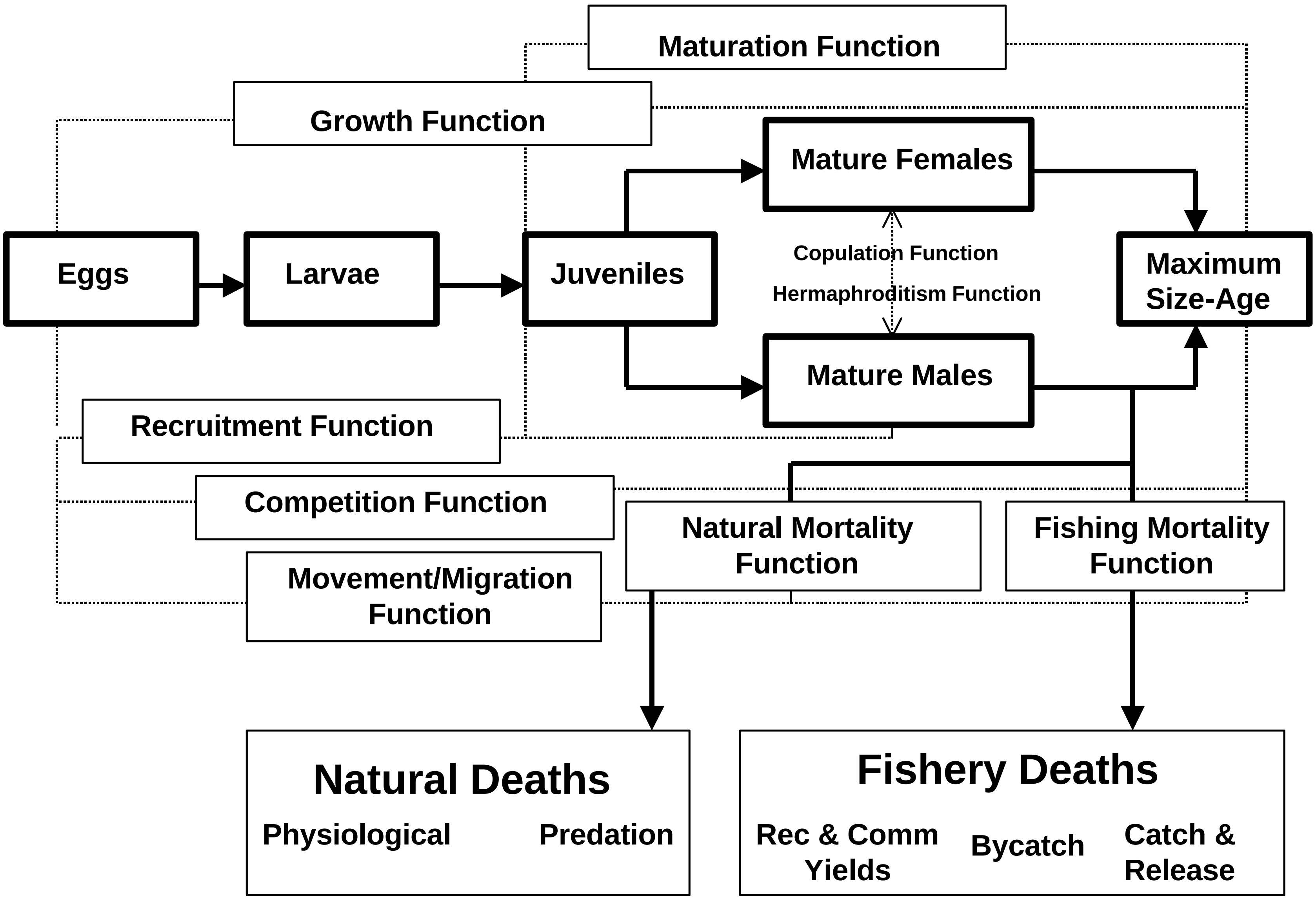

Figure 4.2.- Conceptual overview of the REEFS length-based age- and sex-structured population simulation model used for hogfish stock assessment in the Florida coral reef ecosystem.

Table 4.2.- Results of the REEF analytical yield simulation modeling for Florida hogfish over a range of fishing mortality rates. F is fishing mortality rate, YwPR is yield-per-recruit in kg, SSB is spawning stock biomass, Lbar is average size (cm FL) in the exploitable phase, Wbar is average weight of fish, and SPR is spawning potential ratio.

Florida Hogfish		10/9/03 16:22		**M =**	0.13025						
F	**YwPR**	**SSB**	**Lbar**	**Wbar**	**SPR**	**norm(ypr)**	**slope**	**10% SAO**		**F/Fmsy**	**B/Bmsy**
0		184273		0	1.00000					0.00000	2.8630
0.000001	0.00001	184271	488.17	2284	0.99999	0.00002	14.97	**1.497**		0.00001	2.8630
0.000005	0.00007	184264	488.16	2284	0.99995	0.00011	14.98			0.00004	2.8629
0.0001	0.00150	184090	488.10	2283	0.99901	0.00228	14.96			0.00077	2.8602
0.0005	0.00745	183362	487.82	2279	0.99506	0.01136	14.88			0.00384	2.8489
0.00075	0.01115	182908	487.64	2277	0.99259	0.01699	14.79			0.00576	2.8418
0.001	0.01482	182456	487.46	2275	0.99014	0.02260	14.71			0.00768	2.8348
0.0025	0.03650	179774	486.41	2260	0.97559	0.05564	14.45			0.01919	2.7931
0.005	0.07118	175417	484.67	2237	0.95194	0.10851	13.87			0.03839	2.7254
0.0075	0.10414	171198	482.94	2214	0.92905	0.15875	13.18			0.05758	2.6599
0.01	0.13544	167111	481.23	2191	0.90687	0.20648	12.52			0.07678	2.5964
0.015	0.19342	159316	477.85	2147	0.86457	0.29486	11.60			0.11516	2.4753
0.025	0.29279	145121	471.29	2062	0.78753	0.44635	9.94			0.19194	2.2547
0.035	0.37333	132579	464.98	1983	0.71947	0.56913	8.05			0.26871	2.0599
0.04	0.40760	126858	461.92	1945	0.68842	0.62136	6.85			0.30710	1.9710
0.045	0.43835	121472	458.92	1908	0.65920	0.66824	6.15			0.34549	1.8873
0.05	0.46591	116398	455.99	1873	0.63166	0.71026	5.51			0.38388	1.8085
0.075	0.56533	95032	442.24	1713	0.51571	0.86182	3.98			0.57582	1.4765
0.10	0.61943	78911	429.95	1579	0.42823	0.94430	2.16			0.76775	1.2260
0.10400	0.62517	73774	428.11	1559	0.40035	0.95304	1.43		$F_{0.1}$	0.79846	1.1462
0.11	0.63258	73588	425.42	1531	0.39934	0.96434	1.24			0.84453	1.1433
0.115	0.63777	71129	423.23	1508	0.38600	0.97225	1.04			0.88292	1.1051
0.1155	0.63824	70890	423.01	1506	0.38470	0.97297	0.94			0.88676	1.1014
0.1175	0.64005	69946	422.15	1497	0.37958	0.97573	0.91			0.90211	1.0867
0.12	0.64214	68794	421.09	1486	0.37333	0.97892	0.84			0.92131	1.0688
0.13	0.64877	64466	416.96	1444	0.34984	0.98903	0.66			0.99808	1.0016
0.13025	0.64891	64363	416.86	1443	0.34928	0.98923	0.53		$F_{=M}$	1.00000	1.0000
0.135	0.65116	62460	414.97	1424	0.33895	0.99266	0.47			1.03647	0.9704
0.136	0.65157	62071	414.57	1420	0.33684	0.99329	0.41			1.04415	0.9644
0.14	0.65301	60551	413.02	1404	0.32859	0.99548	0.36			1.07486	0.9408
0.15	0.65528	57002	409.26	1368	0.30933	0.99895	0.23			1.15163	0.8856
0.16	0.65597	53777	405.67	1333	0.29183	1.00000	0.07		F_{max}	1.22841	0.8355
0.17	0.65537	50841	402.24	1300	0.27590	0.99909	-0.06			1.30518	0.7899
0.18	0.65374	48162	398.96	1270	0.26136	0.99659	-0.16			1.38196	0.7483
0.19	0.65127	45712	395.83	1241	0.24807	0.99283	-0.25			1.45873	0.7102
0.20	0.64815	43468	392.83	1214	0.23589	0.98807	-0.31			1.53551	0.6754
0.25	0.62675	34663	379.68	1099	0.18811	0.95545	-0.43			1.91939	0.5386
0.30	0.60207	28662	369.00	1012	0.15554	0.91783	-0.49			2.30326	0.4453
0.40	0.55630	21268	352.81	888	0.11542	0.84806	-0.46			3.07102	0.3304
0.50	0.51959	17049	341.20	806	0.09252	0.79209	-0.37			3.83877	0.2649
0.504	0.50773	16577	340.81	803	0.08996	0.77401	-3.04		F_{2002}	3.86871	0.2576
0.60	0.49092	14398	332.46	747	0.07813	0.74838	-0.17			4.60653	0.2237
0.70	0.46833	12608	325.66	703	0.06842	0.71395	-0.23			5.37428	0.1959
0.80	0.45025	11333	320.21	670	0.06150	0.68639	-0.18			6.14203	0.1761
0.90	0.43554	10386	315.75	643	0.05636	0.66396	-0.15			6.90979	0.1614
1.0	0.42338	9660	312.03	621	0.05242	0.64542	-0.12			7.67754	0.1501
1.1	0.41319	9087	308.88	603	0.04931	0.62988	-0.10			8.44530	0.1412
1.2	0.40453	8625	306.18	588	0.04681	0.61669	-0.09			9.21305	0.1340

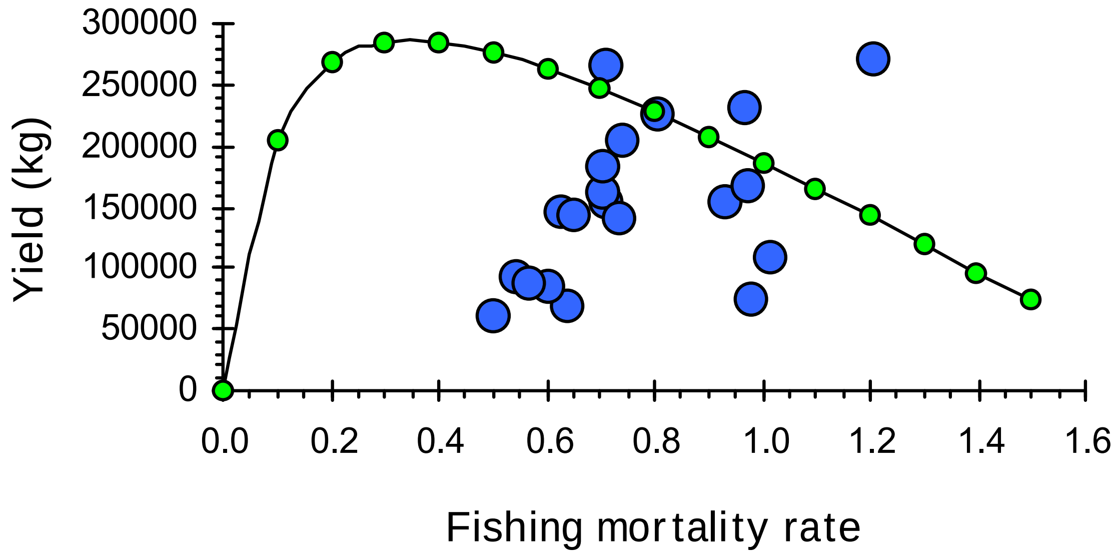

Figure 4.3.- Dynamic catch and fishing mortality for Florida hogfish for the period 1982-2001 over-plotted on the equilibrium yield curve estimated from the age-structured stock synthesis model.

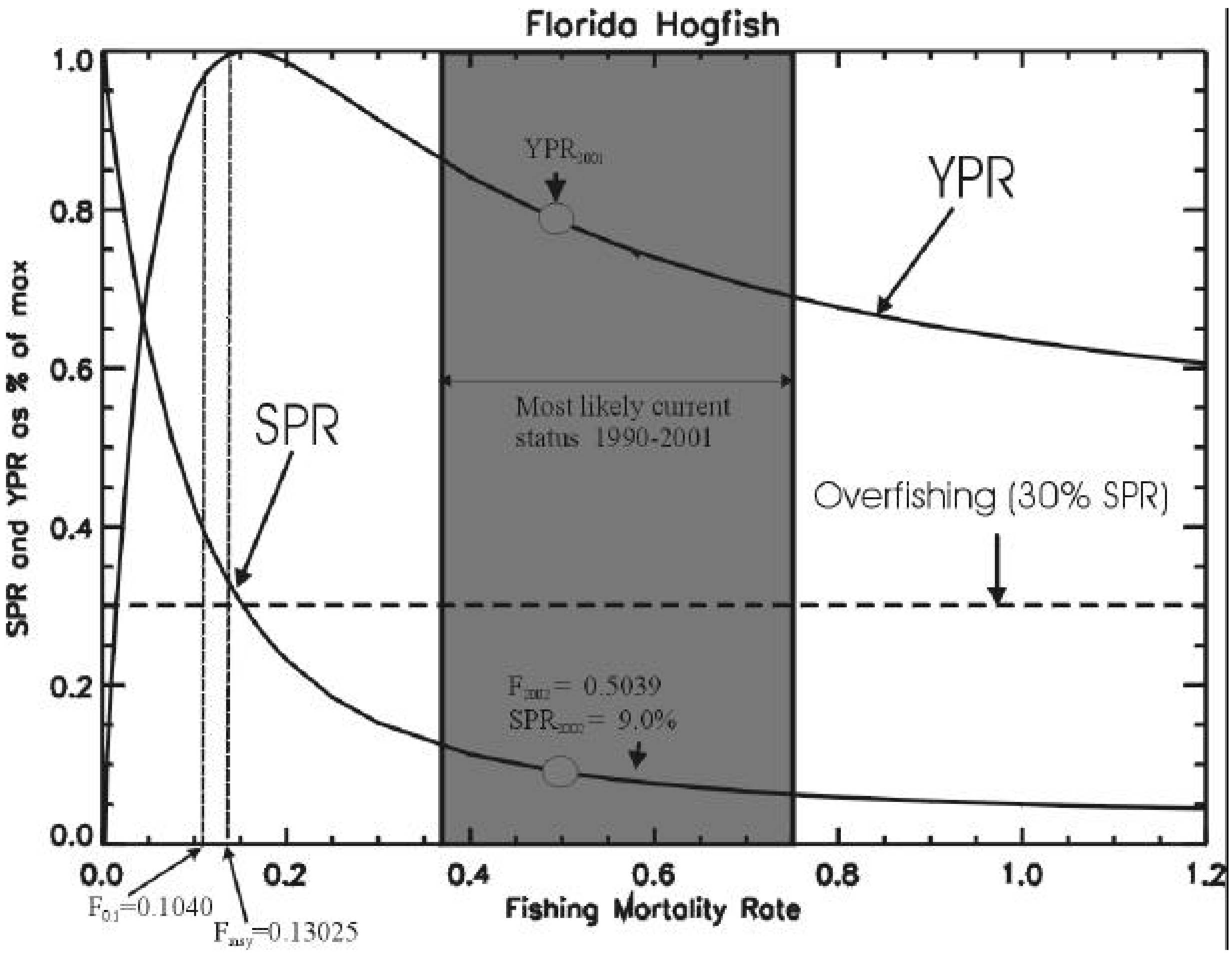

Figure 4.4.- Analytical yield modeling for hogfish showing normalized yield-per-recruit and spawning potential ratio dependent on fishing mortality. Overplotted is the most likely range of estimates for status of the fishery during the period 1990-2002. Shaded area indicates most likely current estimate for the hogfish of F=0.504 has a corresponding SPR of 9.0%, well below the 30% Federal standard for fishery sustainability.

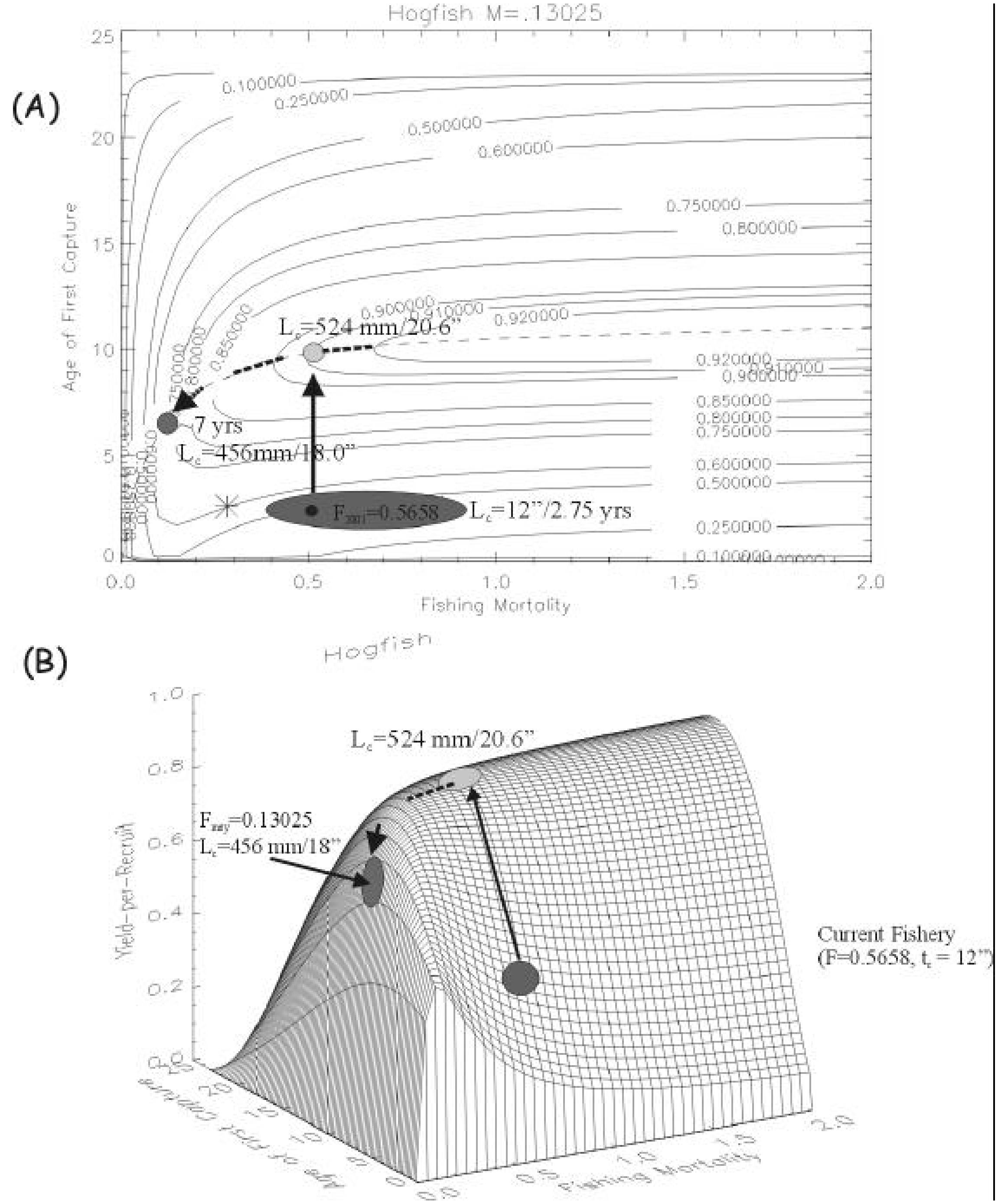

Figure 4.5.- Analytical yield-per-recruit (YPR) analysis for Florida hogfish stock: (a) YPR 2D isopleths; and (b) YPR 3D surface showing current position of the fishery in terms of age (length) at first capture and fishing mortality rate, and optimizing the fishery with respect to minimum age/size of first capture and with respect to both fishing mortality rate and size of first capture.

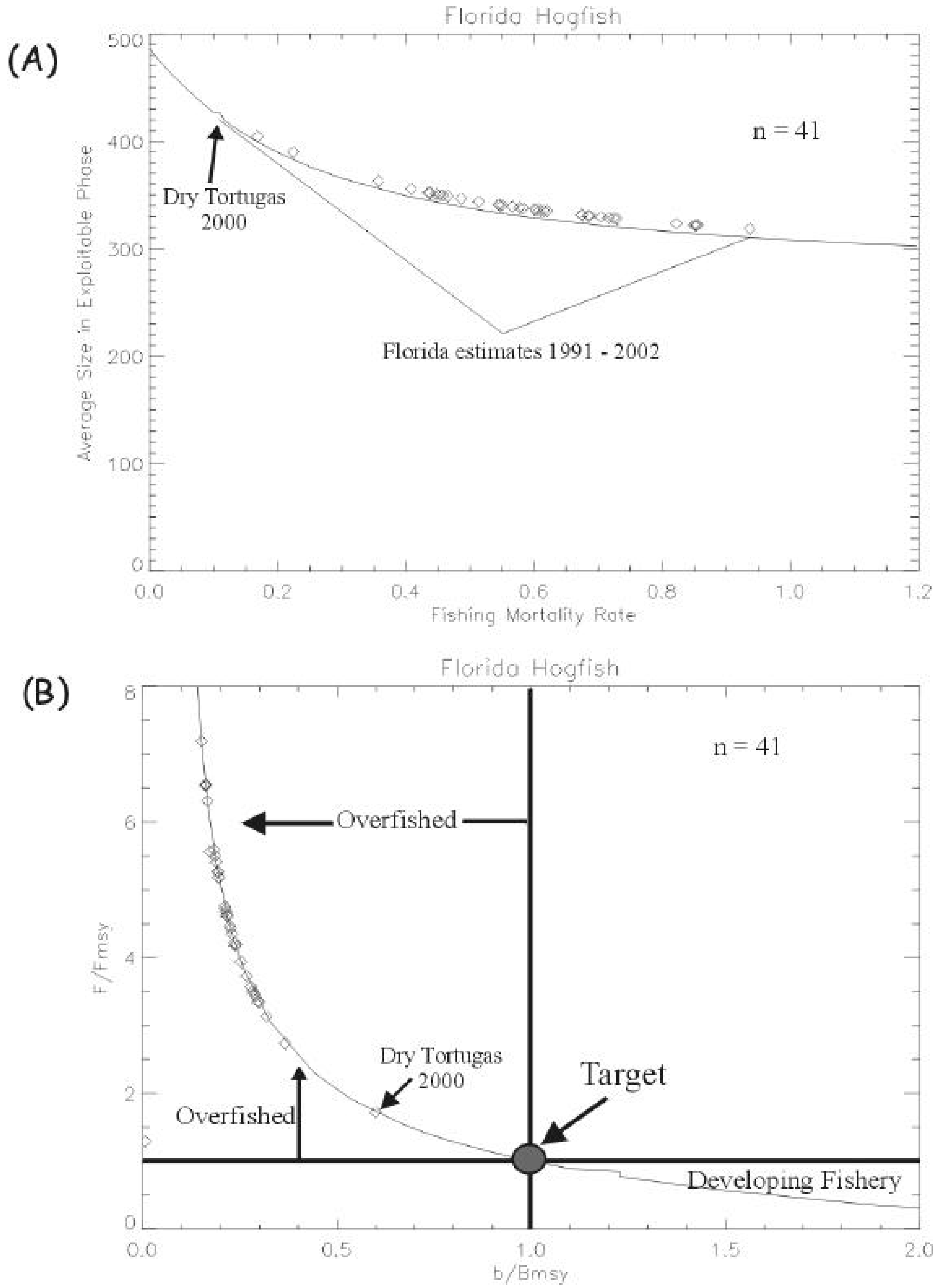

Figure 4.6.- Limit control rule analysis for Florida hogfish: (A) Observations of average size during 1990-2002 plotted against theoretical average size dependent on fishing mortality curve from Ault et al. (1998). (B) Limit control rule analysis for Florida hogfish using estimates of fishing mortality rate and relative stock biomass from data generated from RVC, headboat, Biscayne National Park, MRFSS and Dry Tortugas databases.

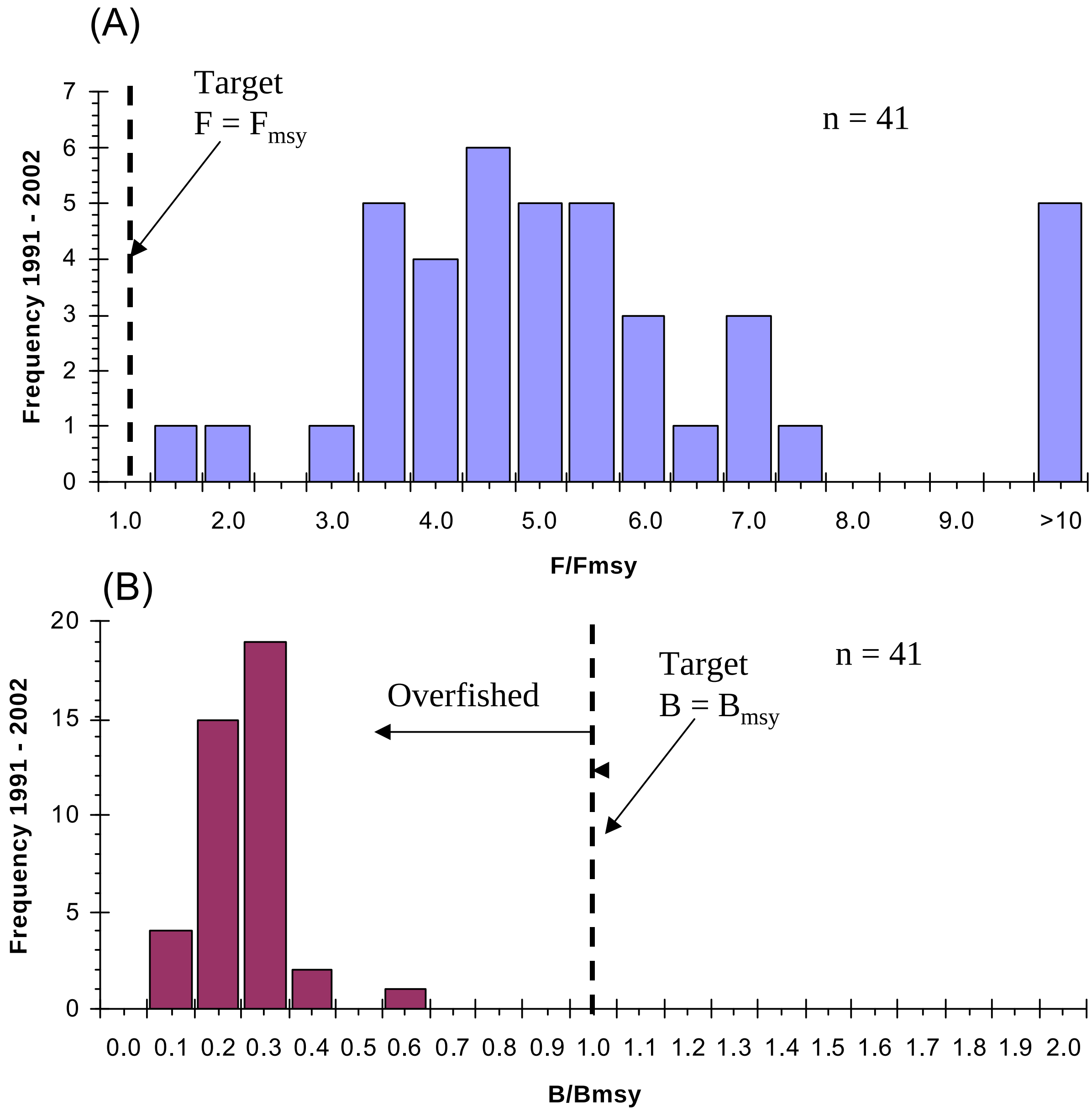

Figure 4.7.- Results of limit control rule analysis for hogfish for 41 observations of fishing mortality from the period 1990-2002: (a) distribution of estimated F/Fmsy; and, (b) distribution of B/Bmsy.

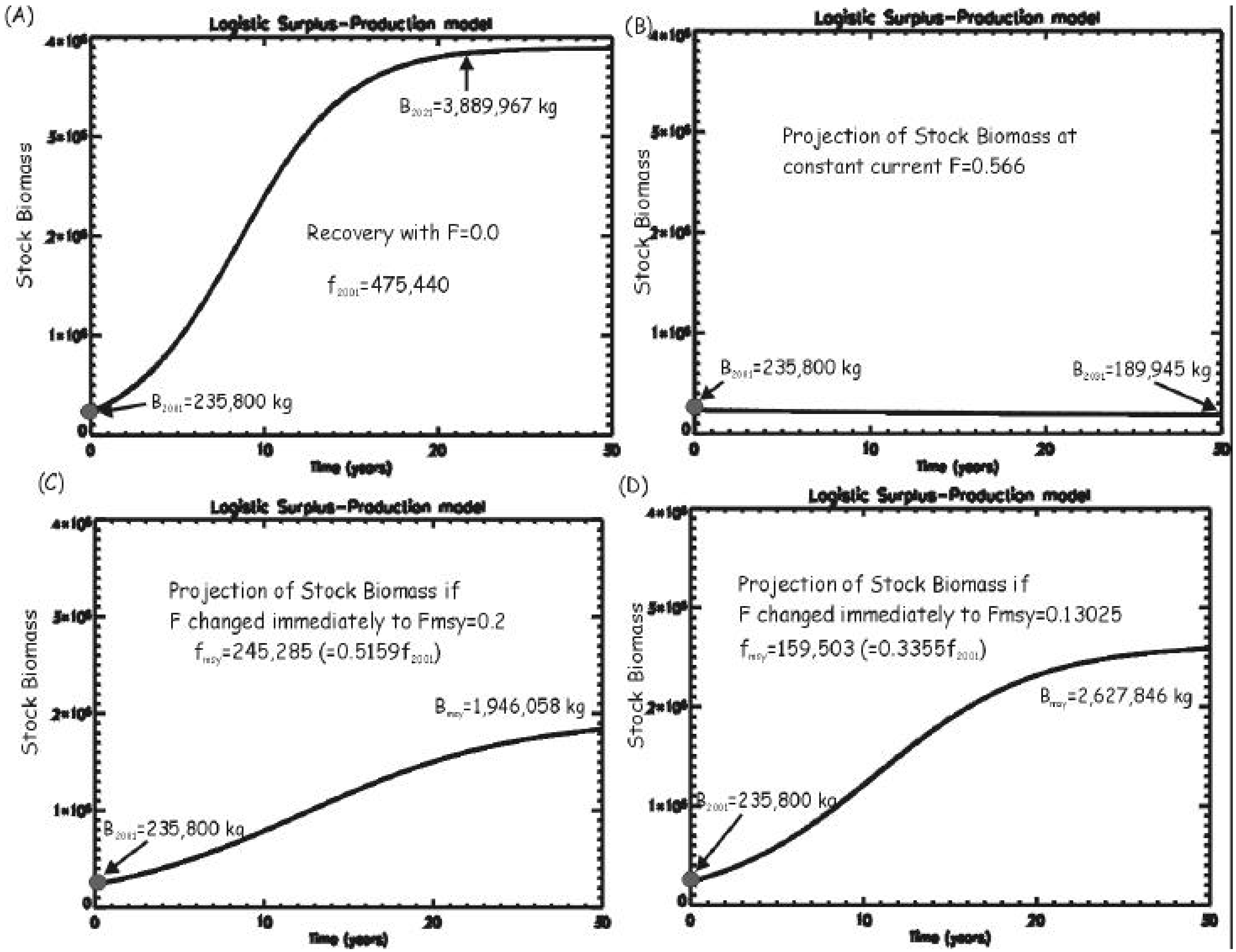

Figure 4.8-Hogfish stock biomass projections using the ASPIC stock production logistic model fits to recreational and commercial fishery data: (A) 30-year time horizon for stock size in 2001 projected forward with no exploitation; (B) projection of stock biomass if the current F=0.566 is held constant; (C) projection of stock biomass if F changed immediately to Fmsy=0.2 (i.e., 48.4% reduction of nominal fishing effort in 2001; and (D) projection of stock biomass if F changed immediately to Fmsy=0.13025 (i.e., 66.5% reduction of nominal fishing effort in 2001).